LINKED DISTURBANCE INTERACTIONS IN SOUTH-CENTRAL ALASKA:

IMPLICATIONS FOR ECOSYSTEMS AND PEOPLE

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LINKED DISTURBANCE INTERACTIONS IN SOUTH-CENTRAL ALASKA: IMPLICATIONS FOR ECOSYSTEMS AND PEOPLE

A

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Abstract

Communities and ecosystems in the Alaskan boreal forest are undergoing substantial change. People contribute to this change. They are also impacted by the consequences. For example, wildfire and spruce bark beetle (*Dendroctonus rufipennis*) outbreaks have increased in frequency and severity due to warming trends, affecting the ecosystem and services important to people. I conducted a study to explore the social and ecological implications of changing natural disturbances.

I evaluated how the occurrence of spruce bark beetle outbreak has altered the probability of wildfire between 2001 and 2009 on the Kenai Peninsula, Alaska. Modeling the effects of bark beetle outbreak on the probability of large wildfire (> 500 ha) and small wildfires (< 500 ha), I found that the influence of the outbreak differed as a function of wildfire size. The occurrence and length of outbreak increased large wildfire probability. Small wildfires were mediated by human influence and less so by bark beetle outbreak.

I also used spatial econometric techniques to estimate how wildfires and the bark beetle outbreak affected property values on the Kenai Peninsula in 2001 and 2010. I found that wildfires > 3.3 ha and the bark-beetle outbreak increased property values. Wildfires < 3.3 ha decreased property values.

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Chapters two and three of this thesis are multi-authored manuscripts prepared for submission or submitted to peer-reviewed journals. Citations corresponding to these chapters and descriptions of my contribution to each are below.

Chapter 2. Hansen, W.D., F.S. Chapin III, H.T. Naughton, T.S. Rupp, and D. Verbyla. Linked Disturbance Interactions in South-Central Alaska: The Effects of a Spruce Bark Beetle (*Dendroctonus rufipennis*) Outbreak on a Changing Boreal Wildfire Regime. Ecological Applications. I developed research questions, conducted research, and wrote the manuscript. My co-authors advised at all steps and helped revise the writing.

Chapter 3. Hansen, W.D. and H.T. Naughton. The Effects of a Spruce Bark Beetle Outbreak and Wildfires on Property Values in the Wildland-Urban Interface of South-central, Alaska, USA. Ecological Economics. I developed the research questions, conducted research, and wrote the manuscript. My co-author advised at all steps and helped revise the writing.

Dedication

This thesis is dedicated to my friends and family who have supported me over the last few years. They patiently listened while I have explored my perspectives, sometimes obstinately, and developed my interests. Thanks so much Mom and Dad, A. Olsson, T. Brinkman, N. Swenson and C. Baughman, T. Jenson, D. Ring, and M. McCleary

Chapter 1

General Introduction

1.1 General Introduction and Context

The human consumption of ecosystem services, or benefits provided to people by the surrounding environment, has led to accelerating rates of social, climate, and ecological change at local-to-global scales (Barnosky et al. 2012, Foley et al. 2005, Vitousek et al. 1997). As the full extent of the consequences related to current human use are gradually recognized, emphasis is increasingly being placed on implementing more sustainable approaches to human-environment interactions (Chapin et al. 2009a, Chapin et al. 2011, Lubchenco et al. 1991). Most recently formulated as ecosystem stewardship, the intention of the initiative is to sustain long-term environmental capacity to provide ecosystem services that support equitable human well-being under conditions of uncertainty and change (Chapin et al. 2010, Folke et al. 2011, Steffen et al. 2011, Westley et al. 2011). However, due to the complexities and contingent, dynamic nature of social and ecological systems, substantial gaps in our conceptual understanding remain that hinder effectively implementing management strategies guided by ecosystem stewardship principles (Armitage et al. 2008, Kofinas 2009, Walker et al. 2002).

Significant resources are currently focused on overcoming these conceptual barriers and important advancements have been made, including the formulation of the social-ecological system (SESs) framework (Berkes & Folke 1998). While the framework has been presented in numerous forms (e.g. Anderies et al. 2004, Chapin et al. 2009b, Collins et al. 2010, Liu et al. 2007, Ostrom 2007), at the core, SESs acknowledge the interdependent, inseparable nature of human well-being and surrounding ecosystems. They are defined as single complex adaptive systems in which humans depend on ecosystem services provided by the surrounding environment and are key drivers of ecosystem structure and function (Berkes & Folke 1998).

While simple in concept, studies suggest that the structure and function of SESs, in practice, are often highly dependent on a vast number of drivers that vary with the conditions and scale of the SES itself (Holling 2001, Walker et al. 2002). Thus, some researchers posit that there are no panaceas--no single framework that can be used to understand all SESs, or universally guide the implementation of ecosystem stewardship-based management strategies (Janssen et al. 2007, Ostrom 2007). However, a number of similarities do exist between different types of SESs. The use of conceptual frameworks, given system-specific context and viewed as a diagnostic tool, may still be of great utility (Ostrom & Cox 2010, Ostrom et al. 2007).

In this introduction, I will adapt an existing SESs framework to better capture social-ecological dynamics in the North American boreal forest. Over the following two chapters, we apply portions of the adapted framework to the boreal forest of the Kenai Peninsula, Alaska and address questions related to complex social and ecological processes. Finally, in the conclusion, I synthesize what is learned from applying the adapted framework to develop generalizable axioms for implementing ecosystem stewardship-based management strategies in boreal systems undergoing social and ecological change.

1.2 Adapting a SESs Framework

Recent advancements in ecological theory suggest that many drivers of ecosystem structure and function can be characterized as either presses or pulses (Folke et al. 2005, Ives & Carpenter 2007, Smith et al. 2009). Presses are drivers that act slowly, persistently, and are often associated with incremental change. Conversely, pulses are drivers that act suddenly, often unpredictably, and with significant consequences for ecosystem structure or function. In the North American boreal forest, the press-pulse distinction nicely characterizes many key ecological drivers, including climate change (press) and wildfire (pulse) (Chapin et al. 2010, Flannigan et al. 2009, Kasischke & Stocks 2000). Further, recognized drivers of social systems often display similar press and pulse characteristics. For instance, cultural norms may have a pressing influence on human well-being, persisting with a small effect, from birth, throughout a person's life. Conversely, the sudden crash of economic markets is more of a pulse-like driver, affecting human well-being unpredictably, with potentially significant consequences from a single event. Scientists propose that the recognition and incorporation of press-pulse dynamics to unify social and ecological systems in a single, comprehensive framework, should facilitate long-term integrated research and may lead to significant improvements in our conceptual understanding of SESs dynamics (Collins et al. 2010, Driscoll et al. 2012).

In this framework, ecosystem structure and function are determined by a suite of press and pulse drivers, such as climate and natural disturbance (Collins et al. 2010).

Human behavior modifies naturally existing presses and pulses as well as creating new ecosystem drivers through processes that include land-use change, active land management (e.g. wildfire suppression) and CO_2 emissions. Presses and pulses determine the nature of ecosystem structure and function and thus, the quality and quantity of ecosystem services that are provisioned for human consumption. These services form the foundation for human well-being (i.e. quality of life, human health, and value systems). Human well-being then shapes human behavior and people's influence on pressing and pulsing drivers of ecosystems. The generalized formulation of the SESs framework uniquely captures a number of important elements for application to the North American boreal system. However, the incorporation of system-specific context by adapting the framework to local conditions is critical and will improve the framework's utility as a diagnostic tool for studying boreal SESs.

The characterization of boreal ecosystem drivers into presses and pulses remains at the core of the adapted framework (Figure 1.1). The effects of presses, like climate change, at high latitudes have been substantial. For example, the mean annual temperature has increased by 2 °C in interior Alaska between 1960 and 2000 (Chapin et al. 2003). As a result, wildfire, the primary natural disturbance, or pulse, has increased in frequency, annual area burned, and severity (Flannigan et al. 2009, Weber & Flannigan 1997, Kasischke et al. 2010). These changes in drivers are likely to have important implications for post-wildfire boreal forest regeneration, boreal tree species assemblages, and may affect the types, quality, and quantity of ecosystem services provisioned (Johnstone & Chapin 2006, Johnstone et al. 2010, Mann et al. 2012).

In boreal SESs, ecosystem services are at the root of human well-being from both a material and emotional perspective (Chapin et al. 2006). Many people living in the boreal forest rely exclusively on fish and game as an available and nutritious source of protein (Loring & Gerlach 2009, Loring & Gerlach 2010, McNeeley & Shulski 2011). Others benefit directly from the extraction of natural resources, including oil and natural gas, forest products, and minerals. Finally, some people live in the boreal system because they appreciate the natural aesthetics associated with living at high latitudes (Brown et al. 2002). However, it is important to note that ecosystems not only provision services, but also disservices (Weitzman 1994). Ecosystem disservices, also known as environmental disamenities, are the negative consequences people experience as a result of their surrounding environment (Mendelsohn & Olmstead 2009). A concept widely accepted in economics, ecosystem disservices in the North American boreal forest include overly-cold winter temperatures, personal and property damage as a result of wildfire, poor ice conditions that hinder winter travel, and the unpredictable or stochastic nature of ecosystems in their capacity to supply critical services (Chapin et al. 2008, Kofinas et al. 2010, Moerlein & Carothers 2012). In the adapted framework, human well-being is not purely related to the benefit of ecosystem services. Instead, well-being is based on trade-offs between the benefits of ecosystem services and the costs of ecosystem disservices. These tradeoffs that form the foundation for human well-being also shape the nature of incentives that determine human behavior and how people influence pressing and pulsing ecosystem drivers.

The general public influences pressing and pulsing drivers with everyday activities in the boreal system (Chapin et al. 2004, Forbes et al. 2004). However, they may not recognize the extent to which their actions affect ecosystem structure and function. Instead, people have developed a suite of social institutions that are trusted to manage ecosystems for the benefit of human well-being (Beier et al. 2009, Trainor et al. 2009). In the adapted framework, people elect public officials closely aligned with their values and interests. People also choose to support companies in the private marketplace, for similar reasons. Institutions, such as government and the private marketplace, then shape policy, whether directly or through market forces, and task ecosystem stewards with implementing that policy. For example, people are normally not responsible for protecting their own home from wildfire. Instead, state and federal government agencies hire fire ecologists to determine how wildfire should be managed ecologically. They hire people to manage wildfire suppression activities and fire fighters to actually fight wildfire. Similarly, an individual does not extract their own fossil fuel for consumption. A company extracts it, processes it, and delivers it to homes and local gas stations.

While ecosystem stewards often receive poignant and direct feedback, particularly from their local community, the creation of tiered institutions responsible for managing ecosystems may act to separate the general public from the ecological consequences of their everyday decisions. Recognizing the role social institutions play in translating well-being into human influence on ecosystems highlights important challenges for implementing ecosystem stewardship-based management strategies. However, the adapted framework also identifies clear opportunities to help people recognize their ecological impact. Further, it provides information on important incentives that can be used to leverage broader public support for novel ecosystem-stewardship strategies.

The SESs framework, adapted for local application to the boreal system, identifies important actors, characterizes the drivers that influence those actors, and highlights critical feedbacks between actors and drivers. Used with a diagnostic approach, this framework could provide substantial insight into complexities of North American boreal SESs and their function. Improving our understanding of SESs dynamics may bolster the implementation of strategies that are meant to alter boreal human-environment interactions and are guided by ecosystem stewardship principles. This could help to foster long-term social-ecological sustainability and engender equitable human well-being; among the current population and for future generations.

1.3 Thesis Chapter Overview

Chapters two and three apply portions of the adapted SESs framework, presented in the introduction, to evaluate complex social and ecological processes on the Kenai Peninsula, Alaska. Chapter two, "Linked Disturbance Interactions in South-Central Alaska: The Effects of a Spruce Bark Beetle (*Dendroctonus rufipennis*) Outbreak on a Changing Boreal Wildfire Regime", examines the extent to which one pulse ecosystem-driver, spruce bark beetle (SBB) outbreaks, influence the characteristics of another, wildfire. Drawing upon a variety of geo-spatial datasets, and applying a relatively new form of statistical analysis, we find that extensive SBB outbreak in the 1990's has increased the probability of subsequent large wildfire activity. Further, the analysis explores how other factors, such as people and climate change, mediate bark beetle-wildfire interactions and the potential consequences of these interactions for an already changing boreal ecosystem.

The third chapter quantifies how the occurrence of two pulse ecosystem-drivers, SBB outbreak and wildfire, and their consequences for ecosystem structure and function, affect property values in the wildland-urban interface (WUI) of the Kenai Peninsula, Alaska. In economics, effects on property values are often used as a proxy measure for the effects of ecological processes on human well-being. While incapable of capturing all aspects of well-being, this approach provides valuable insight into ways in which trade-offs between ecosystem services and disservices ultimately influence well-being and incentivize human behavior. We find that wildfires > 3.3 ha and the occurrence of SBB outbreak are associated with increases in property values, potentially as a result of opening aesthetically pleasing views. This finding suggests that there are unique opportunities for implementing ecosystem stewardship-based strategies for allowing naturally-caused wildfire to burn more regularly. Support for management actions could be bolstered demonstrating to homeowners that targeted fuels reduction treatments around their homes can open up similar views and increase their property values.

Chapter four synthesizes what is learned from applying the adapted framework to processes occurring on the Kenai Peninsula, Alaska and develops generalizable axioms for implementing ecosystem stewardship-based strategies in boreal systems undergoing social and ecological change. Human and climatic pressure on the structure and function of boreal SESs is persistent and increasing. This creates new and important challenges to overcome and presents opportunities to capitalize on. The purpose of this final chapter is to stimulate critical thought on the way in which people of the boreal forest, including the general public, elected officials, corporations, and ecosystem managers, approach their interaction with the surrounding environment and the implications of those interactions for fostering social-ecological sustainability.

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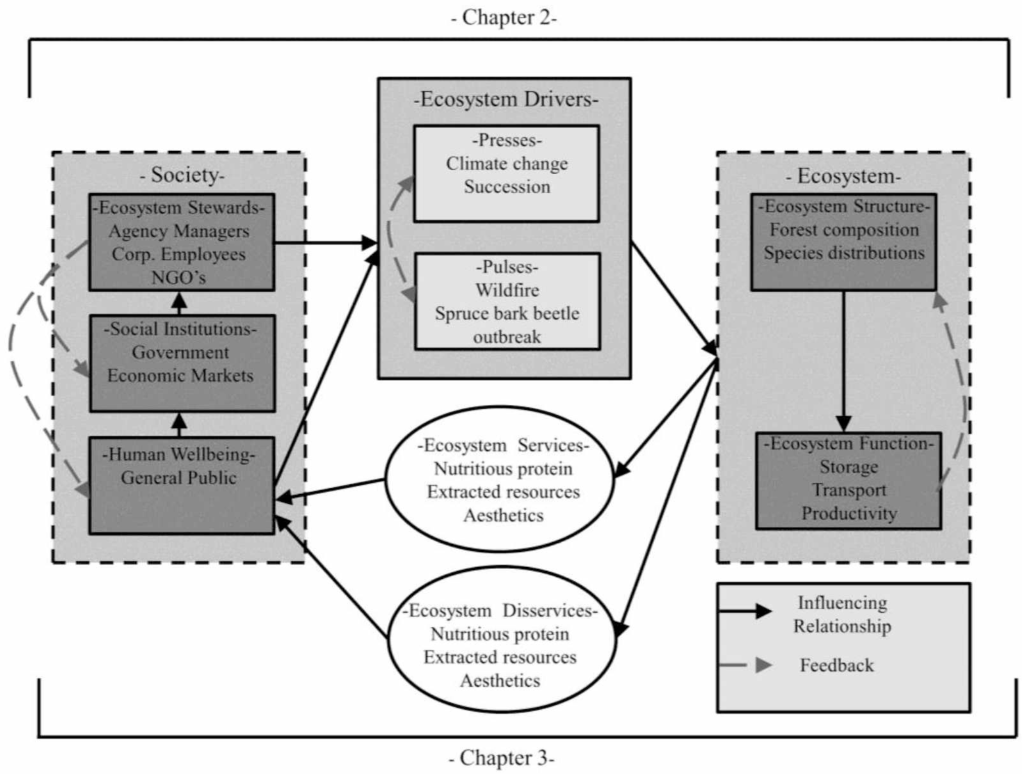

Figure 1.1. Conceptual framework of a social-ecological system adapted from Collins et al. (2010). This version has been adapted to better represent boreal conditions and dynamics. Specific adaptations include differentiating and characterizing the influence of human institutions and incorporating ecosystem disservices in addition to ecosystem services.

Chapter 2

Linked Disturbance Interactions in South-Central Alaska: The Effects of a Spruce Bark Beetle (*Dendroctonus rufipennis*) Outbreak on a Changing Boreal Wildfire Regime[1]

2.1 Abstract

Across the North American boreal forest, warming temperature trends, which are magnified at high latitudes, have led to increases in the frequency, extent, and severity of wildfire. Such changes may have substantial effects on boreal ecosystem structure and function, including tree species assemblages. Although there has been considerable research quantifying the potential effects of warming temperature on boreal wildfire, little is known about how wildfire might interact with other forms of natural disturbance. Between 1989 and 2000, an epidemic spruce bark beetle (SBB) (*Dendroctonus rufipennis*) outbreak occurred on the Kenai Peninsula in south-central Alaska. The objective of this study was to evaluate the extent to which the occurrence and length of the 1990's SBB outbreak has altered the probability of subsequent wildfires between 2001 and 2009. Modeling the effects of SBB outbreak on the probability of large wildfires (> 500 ha) and small wildfires (< 500 ha) independently, we found that the influence of the outbreak differed as a function of wildfire size. The occurrence and length of the 1990's SBB outbreak increased the probability of large wildfires. The magnitude of the outbreak's effects was only exceeded by dominant vegetation type. Conversely, small wildfires were largely mediated by human influence and less by the

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1990's SBB outbreak. Past research on historical bark beetle-wildfire interactions on the Kenai Peninsula and studies in the western United States have found that bark beetles have very different effects on subsequent wildfire. We compare our findings with these past studies to identify potential management-relevant mechanisms that may explain these differences and discuss their implications. Our results suggest that the effects of increasing temperature on boreal wildfire may be amplified when in interaction with SBB outbreaks.

2.2 Introduction

As a consequence of climate change, natural disturbance regimes are increasingly diverging from their historical ranges of variation (Flannigan et al. 2000, Overpeck et al. 1990, Turner 2010, Westerling et al. 2006). As relatively discrete events that alter the structure of populations, communities, or ecosystems, natural disturbances are often primary drivers of successional trajectories and can foster ecosystem heterogeneity (Peters et al. 2011, Turner et al. 1998, Turner et al. 2003, White and Pickett 1985). Thus, accounting for the impacts of changing natural disturbance regimes may be integral to effective ecosystem management (Swanson and Chapin 2009).

While climate is a critical driver of natural disturbance, characteristics and processes of the system in which natural disturbance acts are also important (Westerling et al. 2011). For example, the occurrence of one type of natural disturbance in a system can change the frequency, extent, and severity of other types, a concept known as linked disturbance interactions (Simard et al. 2011). Thus, the effects of climate change on natural disturbance, the resulting ecological consequences, and their implications for ecosystem management are likely to differ among systems (Dale et al. 2000).

Across the North American boreal forest, warming temperature trends, which are magnified at high latitudes, have led to increases in the frequency, extent, and severity of wildfire (Flannigan et al. 2009, Weber and Flannigan 1997). Studies estimate that, by the end of the 21st century, annual area burned in the North American boreal forest may expand by 74 to 118 percent (Balshi et al. 2008, Flannigan et al. 2005). Changes to the wildfire regime could disrupt feedback cycles that determine the nature of forest regeneration and tree species assemblages (Johnstone and Chapin 2006, Johnstone et al. 2010, Mann et al. 2012). Research has been conducted to quantify potential effects of warming temperature on boreal wildfire. However, additional factors, such as linked disturbance interactions, have yet to be incorporated.

Bark beetles are another important boreal natural disturbance that responds to warming temperatures (ACIA 2005, Berg et al. 2006, Raffa et al. 2008, Sherriff et al. 2011, Werner and Holsten 1985, Werner et al. 2006). In the white and Lutz spruce (*Picea glauca, Picea lutzii*) stands of the western Kenai Peninsula in south-central Alaska, a series of warm summers led to a spruce bark beetle (SBB) (*Dendroctonus rufipennis*) outbreak that extended over 1.2 million ha between 1990 and 2000. SBBs killed an estimated 30 million trees per year (Berg et al. 2006, Werner et al. 2006).

Past SBB outbreaks have occurred, on average, once every 50 years on the Kenai Peninsula. Historical outbreaks are thought to have not influenced wildfire. However, due to the high severity of the 1990's SBB outbreak and continued warming temperatures, concern emerged that the outbreak has amplified wildfire risk (Berg and Anderson 2006). To improve our understanding of how SBB outbreaks are likely to further influence a changing boreal wildfire regime, we asked, to what extent has the occurrence and length of the 1990's SBB outbreak on the western Kenai Peninsula, Alaska affected the probability of subsequent wildfire between 2001 and 2009?

Research on bark beetle-wildfire interactions in the Rocky Mountains of the western United States, has produced varied results. Bark beetle outbreaks in a pine (*Pinus contorta*), spruce (*Picea engelmaanii*) and fir *(Abies lasiocarpa*) mixed forest of Colorado were associated with no increases in the extent or severity of subsequent wildfire (5 to 50 years later) (Bebi et al. 2003, Bigler et al. 2005, Kulakowski and Veblen 2007, Kulakowski and Jarvis 2011,). However, in the same study area, Bigler et al. (2005) reported small increases in wildfire severity 60 years post-bark beetle outbreak. Bark beetle outbreaks were associated with a decreased probability of active crown fire in lodgepole pine (*Pinus contorta*) and Douglas-fir (*Pseudotsuga menziesii*) stands in northwestern Wyoming; likely due to a reduction in canopy bulk density (Donato et al. 2012, Simard et al. 2011). Further, little change in the build-up of surface fuels has been conclusively documented up to 40 years post-bark beetle outbreak, with the exception of 1000-hour fuels (Donato et al. 2012, Schoennagel et al. 2012, Simard et al. 2011).

On the western Kenai Peninsula, increases in both the height and density of 1-, 10-, 100-, and non-rotting 1000-hour surface fuels were documented following the

1990's SBB outbreak (Schulz 1995, 2003). Understory moss depth decreased, indicative of drying microclimates. *Calamagrostis canadensis* (blue joint grass) also proliferated extensively in some spruce stands affected by the 1990's SBB outbreak (Goodman and Hungate 2006, Boggs et al. 2008). Calamagrostis is a native early post-disturbance colonizer in the boreal forest that can form a thick surface mat of dead litter (Lieffers et al. 1993). Dry surface litter acts as a "flashy" fuel prior to green-up and after senescence during late summer (Schulz 1995).

The 1990's SBB outbreak led to changes in surface-fuel loads that suggest the potential for increased wildfire risk. However, there are a number of additional factors that may have influenced the extent to which the probability of wildfire has actually been affected. For example, people are the primary source of ignition on the western Kenai Peninsula, an area where access is concentrated to a relatively limited road network. All human-caused fires are suppressed in the region (Morton et al. 2006). While wildfires are more likely to ignite in areas easily accessible to people, these fires also may be smaller (DeWilde and Chapin 2006). Thus, the determinants of small wildfire probability on the western Kenai Peninsula may differ from those that determine the probability of large wildfires.

Our first objective was to evaluate the extent to which the occurrence and length of the 1990's SBB outbreak has altered the probability of subsequent wildfire, between 2001 and 2009, on the western Kenai Peninsula, Alaska. Secondly, we wanted to determine whether the relationship between the SBB outbreak and subsequent wildfire differed as a function of wildfire size. We hypothesized the buildup of surface fuel loads would be important for predicting the probability of large wildfires and there would be a higher probability in forest stands (1) that were affected by the SBB outbreak and (2) that were affected by the SBB outbreak for a longer time. Conversely, we hypothesized that the probability of small wildfires would primarily be determined by the extent of human land use. We hypothesized that the locations of small wildfires would (1) correspond closely to the road network and (2) be more likely on lands designated for active wildfire suppression.

2.3 Methods

2.3.1 Study Area

The western Kenai Peninsula of south-central Alaska extends from Cook Inlet on the west, to the Kenai Mountains on the east, and sits south of Anchorage, Alaska (Figure 2.1). The western Kenai lies at the southern extent of the physical and ecological conditions that characterize the Alaskan boreal forest. Mean annual precipitation varies from 369 mm in northwestern Kenai Peninsula to 650 mm at the southern extent (1971-2000) (Western Regional Climate Center 2012). Average annual temperature is relatively consistent across the study area at approximately 1 °C. Coastal forests comprise Lutz and sitka spruce (*Picea sitchensis*). Interior stands are dominated by white spruce (*Picea glauca*) and resin birch (*Betula neoalaskana*). For the purposes of analysis, we excluded all lakes and incorporated city limits within the study area.

2.3.2 Data

Both wildfire and SBB outbreaks are discrete events. For example, a pixel either experienced a natural disturbance, or it did not. Analyses of discrete events often take the form of binary logistic regression where the probability of wildfire occurring (value of one) versus not occurring (value of zero) is modeled as a function of a suite of independent variables. However, when datasets have many more non-event observations (zeros) than event observations (ones), binomial logistic regression can underestimate the probability of rare events, such as wildfire (King and Zeng 2001). To overcome this limitation of binary logistic regression, a variation has been developed called Rare Events Logistic Regression (RELR). This approach pairs all the event observations in the dataset with a random selection of the non-event observations (King and Zeng 2001).

We used a geographic information system (GIS) and a form of RELR to model the probability of large wildfires and small wildfires between 2001 and 2009. Independent variables included the occurrence and length of 1990's SBB outbreak, previous fire history between 1947 and 2000, average fire-season potential aridity between 2001 and 2009, vegetation flammability and structure, aspect, land use, and fire suppression policy. We entered these spatially explicit data into a GIS and resampled them using ArcGIS Desktop 10.0 (ESRI 2011). This yielded 14,141 *1 km by 1 km* pixels in the study area that we used as observations in our analyses.

The occurrence of large wildfire was defined as any pixel that fell within the perimeter of a wildfire larger than 500 ha between 2001 and 2009 (Figure 2.2). There were 11 large wildfires that occurred in the study area between 2001 and 2009 that burned 3.8 percent of the study area. Data on large wildfires and small wildfires, between 2001 and 2009, as well as previous wildfire history since 1946, were derived from two datasets in the Alaska Fire Service's Fire History Database (Alaska Fire Service 2012). The dataset, from which information on large wildfires and past fire history were derived, includes digital fire perimeter maps that were developed using a combination of field-based and aerial surveys and the interpretation of aerial and satellite-based imagery (Kasischke et al. 2002). The small wildfire dataset represents fires as point locations and we defined small wildfire as any sampled pixel within which the recorded origin point of a wildfire, smaller than 500 ha, fell between 2001 and 2009 (Figure 2.2). There were 324 small wildfires that were included in our sample, of which approximately 97 percent were within 10 km of a road (Figure 2.2).

People are the primary cause of wildfire ignition on the Kenai Peninsula. The majority of human-caused wildfires occur close to roads (DeWilde and Chapin 2006, Calef et al. 2008). To account for people as an ignition source, we included distance from the nearest road in our statistical analyses. Wildfire suppression influences whether wildfires spread from one pixel to another. We included a variable to account for the designated wildfire suppression option. State and federal agencies responsible for wildfire suppression in Alaska have delimited the state into four fire management options ranging from critical and full suppression, where many people live and wildfires are immediately attacked, to limited suppression, in areas where few people live and human-caused wildfires are rare. Naturally caused wildfires in limited suppression zones are allowed to burn unless they threaten life or property (Alaska Wildfire Coordinating Group 1998). Human-caused wildfires in limited suppression zones are suppressed. In our analyses, we included a variable to differentiate pixels that fell within the top two suppression classifications, critical and full.

The U.S. Forest Service and Alaska Department of Natural Resource's Alaska Forest Health Protection Program mapped polygons delimiting the 1990's SBB outbreak, throughout the study area, from 1989 to 2000 (Figure 2.2) (United States Forest Service and Alaska Department of Natural Resources 2012). Aerial surveys were conducted annually on the Kenai Peninsula during the 1990's outbreak. These surveys were meant to provide information on general trends in SBB outbreak progression at a regional scale. 75% of the area burned by large wildfires was located within SBB outbreak perimeters.

SBB outbreaks differ from wildfire in that they can persist for several successive seasons. While, in general, studies on linked disturbance interactions have evaluated how the *occurrence* of a bark beetle outbreak influences subsequent wildfire, cumulative effects related to the *length of the outbreak* may influence the magnitude of interaction and provide further insight. Thus, in addition to accounting for the occurrence of SBB outbreak in a given pixel, we also developed an index of SBB outbreak length. The index varied between zero and one in a given location, zero being no outbreak and one being the maximum outbreak length (9 years) observed.

We used the 2001 Multi Resolution Land Consortium's National Land Cover Database to account for vegetation flammability and canopy structure (Homer et al.

2004). Vegetation data provided information on the dominant canopy tree species above five meters tall in forested areas and designated shrublands and grasslands in non-forested areas. Our vegetation variable differentiated between more flammable and less flammable vegetation types. In this analysis, pixels that were recorded in the NLCD as conifer, upland grasslands, or upland shrublands were classified as more flammable vegetation. Less flammable vegetation included upland mixed forest and lowland wetlands. Stand structure was represented in the analysis as percent tree cover from the NLCD database.

Aspect was derived from a 60 m digital elevation model. Average 2001-2009 fire season (May-August) potential aridity, measured as precipitation minus potential evapotranspiration (P-PET), was calculated using gridded historical CRU TS 3.1 0.5° x 0.5° temperature data and CRU TS 3.1.01 0.5° x 0.5° precipitation data (Jones and Harris 2008, Mitchell and Jones 2005). Scenarios Network for Alaska and Arctic Planning downscaled the data to approximately a 1 km resolution with the delta methodology and calculated PET using the Hamon equation (SNAP 2012). P-PET incorporates precipitation with evaporative demand, driven by temperature, to provide an estimate of seasonal surface fuel moisture content and flammability.

2.3.3 Analysis

With the statistical software R and packages Zelig, MASS, and car, we used a variation of RELR, known as Rare Event Logistic Regression with Replications (RELRR), to model the probabilities of large wildfire and small wildfires as a function of independent variables (Fox and Weisberg 2011, Guns and Vanacker 2012, Imai et al. 2006, R Development Core Team 2012, Venables and Ripley 2002). In RELR, a choice-based or case-control sampling design is employed (Breslow 1996, Ramalho 2002). All the event observations (n) in the dataset are included in the model with a random selection of $10n$ non-event observations. It has been shown that this sampling strategy may lead to a biased estimation of the equation's intercept term (King and Zeng 2001). Thus, a prior correction is made based on the fraction of event observations in the population and the fraction of event observations in the dataset subsample (King and Zeng 2001). While originally developed for application in political science, a number of studies have used the approach to model natural hazards (Bai et al. 2011, Van Den Eeckhaut et al. 2009, Vanwalleghem et al. 2008).

However, recent advancements question the robustness of results from RELR, showing that coefficient estimates may be dependent on the random sample of non-event observations chosen (Guns and Vanacker 2012). To overcome this limitation, RELRR improves estimation robustness by averaging the results of multiple RELR runs on several pairings of the event observations with different random subsamples of the non-event observations (Guns and Vanacker 2012). RELRR provides a more comprehensive understanding of variable influence by combining statistical measures of significance with probabilistic information on variable importance. In this paper, we applied the RELRR approach to independently model the probabilities of large wildfires and small wildfires between 2001 and 2009. Independent variables included the occurrence and length of the 1990's SBB outbreak, percent canopy cover, vegetation flammability, P-PET, aspect, distance to nearest road, and fire management option.

First, we evaluated multicollinearity among independent variables for both the large wildfire and small wildfire datasets ensuring they had a variable inflation factor (VIF) below two. Due to multicollinearity (VIF > 2), we could not include variables for both the occurrence and length of SBB outbreaks in a single statistical analysis. Therefore, we analyzed the effects of each independently. To accomplish this, we paired all of the event observations (*n*) in the large wildfire dataset (i.e. pixels that fell within the perimeter of a large wildfire) with 100 different randomly chosen sets of 10*n* non-event observations (i.e. pixels where no large wildfire occurred). We did the same with the small wildfire dataset (Beguería 2006, Guns and Vanacker 2012). There were 499 event observations for the large wildfire dataset and 324 for the small wildfire dataset. We then conducted RELRR using 50 of these subsamples from each of the two wildfire datasets to evaluate the influence of the SBB outbreak occurrence (outbreak occurrence analyses [OOA]) on the probabilities of small and large wildfires. The other 50 subsamples of each wildfire dataset were used to evaluate the influence of SBB outbreak length (outbreak length analyses [OOL]) on the probabilities of small and large wildfires. Variable coefficients were calculated as the average parameter estimate from regression runs on the 50 subsamples in which the variable had a statistically significant effect on the probability of wildfire ($p<0.05$). We also calculated the percent of regression runs in which the variable was significant (% sig). To ensure clear interpretation, coefficients are presented as odds ratios which describe how a one unit change in the independent variable influences the odds of a wildfire occurring, holding the other variables equal. Moran's I was used to evaluate spatial autocorrelation among model residuals.

2.4 Results

The occurrence (i.e., pixel classified as experiencing an outbreak) of the 1990's SBB outbreak was an important predictor of large wildfire probability when other variables were held constant. The odds of large wildfire were 4.66 times higher, when SBB outbreak had occurred, as compared to pixels that did not experience outbreak. The occurrence of SBB outbreak was statistically significant in 100% of the outbreak occurrence analyses (OOA; % sig = 100, $p < 0.01$) (Table 2.1). Additionally, there were cumulative effects associated with the number of years that the outbreak persisted. The extent to which the probability of subsequent large wildfire increased, when SBB outbreak occurred in a given pixel, was amplified by the length of that outbreak (OLA; % sig = 100, $p < 0.01$) (Table 2.2).The odds of large wildfire were 4.1 times higher when the outbreak length index increased by its standard deviation (0.32).

P-PET was also an important predictor of large wildfire. For a standard deviation *decrease* in P-PET (31.3 mm) the odds of large wildfire increased by 1.87 times, holding all other variables constant (OOA & OLA; % sig = 100, $p < 0.01$) (Table 2.1 & Table 2.2). The probability of large wildfire showed no correlation with past wildfire occurrence (1946-2000), a very small positive correlation with percent canopy cover (OOA; % sig = 96, $p < 0.05$, OLA; % sig = 62, $p < 0.05$), and a strong positive correlation with more flammable vegetation (i.e. coniferous forest, upland grassland, or shrubland)

(OOA & OLA; % sig = 100, $p < 0.01$), distance from the nearest road (OOA & OLA; % sig = 100, $p < 0.01$) and aspect (north/south facing) (OOA & OLA; % sig = 100, $p < 0.01$) (Table 2.1 & Table 2.2). In the SBB outbreak occurrence analyses, pixels with a full or critical wildfire suppression classification had a higher probability of large wildfire (OOA; % sig = 100, $p < 0.01$) (Table 2.1). However, the variable was largely unimportant in the SBB outbreak length analyses (OLA; % sig = 2, $p < 0.05$). Spatial autocorrelation between model residuals was present in both the SBB outbreak occurrence and length analyses ($p < 0.01$).

Many factors had a very different effect on the probability of small wildfires as compared to how they influenced large wildfire probability. For example, as compared to its influence on the probability of large wildfire, the occurrence of the 1990's SBB outbreak was far less important for predicting small wildfires. In analyses where the occurrence of SBB outbreak was statistically significant, the variable was negatively correlated with the probability of small wildfires. Odds of a small fire in a pixel *not affected* by the SBB outbreak were 1.4 times higher than in pixels that experienced SBB outbreak (OOA; % sig = 48, $p < 0.05$) (Table 2.3). The effect of SBB outbreak length on the probability of small wildfires was typically statistically insignificant and small in magnitude (OLA; % sig = 20, $p < 0.05$) (Table 2.4).

Distance from the nearest road was negatively associated with the probability of small wildfires: opposite to the variable's influence on the probability of large wildfire. The odds of small wildfires were 12.8 times higher in pixels that were located a standard deviation (8.23 km) *closer* to a road than other pixels, holding all other variables constant (OOA & OLA; % sig = 100, $p < 0.01$) (Table 2.3 & Table 2.4). A full or critical fire suppression classification was largely statistically insignificant in both the SBB outbreak occurrence and length analyses (OOA; % sig = 28, OLA; % sig = 14, $p < 0.05$) (Table 2.3 & Table 2.4). However when significant, the odds of small wildfires were 1.5 times higher in pixels classified for full or critical suppression.

Other variables also differed in their influence on the probability of small wildfires, as compared to their effect on the probability of large wildfire. The occurrence of past wildfire (1946-2000) was negatively associated with the probability of small wildfires (OOA & OLA; % sig = 100, $p < 0.01$) (Table 2.3 & Table 2.4). Further, the probability of small wildfires displayed a very small negative correlation with percent tree cover (OOA; % sig = 32, OLA; % sig = 38, $p < 0.05$), and was not correlated to north-facing aspect (Table 2.3 & Table 2.4). A few variables had similar effects in the small-wildfire and large-wildfire analyses. The probability of small wildfires was positively correlated with P-PET (OOA & OLA; % sig = 100, $p < 0.01$) and south-facing aspect (OOA & OLA; % sig = 92, $p < 0.01$) (Table 2.3 & Table 2.4). Spatial autocorrelation between model residuals was not present in any statistical analyses of the small wildfire dataset ($p > 0.05$).

2.5 Discussion

This study improves our understanding of how wildfire has responded to an extensive 1990’s SBB outbreak in the boreal forest of the western Kenai Peninsula, Alaska. Confirming our hypotheses, we found that the occurrence and length of the 1990's SBB outbreak increased the probability of large wildfire. However, the outbreak had little to no influence on the probability of small wildfires. Instead, people appear to be the primary driver, as a source of ignition and by suppressing wildfire. In the context of other studies on bark beetle-wildfire interactions, our results highlight the complex and contextual nature of linked disturbance interactions. Further, they improve our understanding of how boreal wildfire may respond to a changing climate in a more comprehensive context.

2.5.1 Large Wildfire

The occurrence and length of the 1990's SBB outbreak increased the probability of large wildfire on the western Kenai Peninsula. The magnitude of the outbreak's influence was second only to vegetation flammability. This finding contradicts research conducted on bark beetle-wildfire interactions in other systems as well as work conducted on historical bark beetle-wildfire interactions in the study area (Bebi et al. 2003, Berg and Anderson 2006, Donato et al. 2012, Kulakowski and Veblen 2007, Simard et al. 2011). Several factors may explain why the probability of large wildfire increased in spruce stands of the western Kenai Peninsula affected by 1990's SBB outbreak (Figure 2.3).

Bark beetle outbreaks in the Rocky Mountains of the western United States have had little to no influence on subsequent wildfire occurence; and in some cases, reduced the probability of active crown fire (Bebi et al. 2003, Kulakowski and Veblen 2007, Simard et al. 2011). One potential explanation is that there has been little increase in surface fuel loads, other than the increase in 1000-hour fuels after bark beetle outbreaks in the Rocky Mountains (Donato et al. 2012, Schoennagel et al. 2012, Simard et al. 2011). Conversely, following the occurrence of 1990's SBB outbreak on the western Kenai Peninsula, increases in surface fuel loads and height were documented for 1-, 10-, 100-, and non-rotting 1000-hour fuel classes (Schulz 1995, 2003). The cumulative effects associated with longer SBB outbreaks may further amplify the accrual of surface fuel loads. Calamagrostis, an early successional dominant species, also proliferated extensively in some SBB affected white spruce stands of the western Kenai Peninsula (Boucher and Mead 2006, Holsten et al. 1995, Lieffers et al. 1993, Schulz 1995). The grass can form a thick mat of dead litter that acts as a fine "flashy" surface fuel (Holsten et al. 1995). Increases in the availability of surface fuels likely play a key role in the spread of boreal wildfire (Weber and Flannigan 1997). However, with the exception of Calamagrostis, the reasons why surface fuel loads increased following bark beetle outbreak on the western Kenai Peninsula, and not in the Rocky Mountains, remain unclear.

Historical SBB outbreaks on the western Kenai Peninsula appear to have not been associated with increases in the probability of subsequent wildfire (Berg and Anderson 2006). Historically, up to ten cycles of SBB outbreaks occurred during one fire cycle. However, the boreal wildfire regime is changing as a consequence of warming temperatures (Kasischke and Turetsky 2006). Similar warming trends have been documented on the western Kenai Peninsula. Over the last four decades, May through September temperatures, recorded at the Kenai airport, have increased 0.73 °C and are projected to continue warming (ACIA 2005, Berg et al. 2009). We found that potential aridity, driven by warmer temperatures, increased the probability of large wildfire. The 1990's SBB outbreak may now influence wildfire in fundamentally different ways than historical outbreaks by amplifying the effects that warming temperatures are already having on the probability of large wildfire. Amplified warming as a result of bark beetle outbreak has been documented elsewhere. Due to a reduction in plant transpiration, forest surface temperatures were estimated to be 1 °C higher in bark beetle outbreaks of British Columbia as compared to non-affected stands (Maness et al. 2012). The presence of linked disturbance interactions on the western Kenai Peninsula, when there is little evidence of historical precedent, raises important questions regarding the dynamic nature of linked disturbance interactions and how system-specific drivers mediate those interactions.

2.5.2 Small Wildfires

In contrast to their influence on the probability of large wildfire, the occurrence and length of SBB outbreak were less important in predicting the probability of small wildfires. Instead, distance from the nearest road, past wildfire history, and potential aridity were key determinants.When SBB outbreak occurrence and length were significant in statistical analyes, the relationship was negative. People play an important role determining the characteristics of wildfire across the boreal forest (Chapin et al. 2003). They may alter the nature and magntiude of linked disturbance interactions by causing more frequent wildfire than would naturally occur and by reducing wildfire size through active suppression.

In interior Alaska, between 1992 and 2001, there were 50 times more fires, the fire season began two months earlier, and there was a 50% reduction in the proportion of area burned on lands designated for suppression as compared to those where wildfire burned naturally (DeWilde and Chapin 2006). On the Kenai Peninsula, the probability of small wildfires decreased with distance from roads, while the probability of large wildfires increased. This suggests that small wildfires were more likely to occur, get reported, and be actively suppressed, keeping them small, in forest stands frequented by people. These results are supported by the fact that significant resources were expended, following the SBB outbreak, to develop community wildfire protection plans along the road network. By keeping wildfires small, through suppression, people alter the extent to which the SBB outbreak is linked to, and interacts with, wildfire.

When the occurrence and length of the 1990's SBB outbreak were signficant, the outbreak reduced the probability of small wildfires. This is counter-intuitive as one might expect the build up of surface fuels, particularly fine fuels, to increase the risk of human-caused wildfire ignition. One explanation may be that wildfires in SBB outbreak became large, and once burned, reduced the probability of subsequent small wildfires. However, large wildfires following the outbreak only burned about 3.8 % of the study area. Further, small wildfires are predominatly located along the road network (Map 2.2 b). A more likely explanation is that many people on the Kenai Peninsula felt a sense of emotional distress and sadness related to the loss of their forests and the changing aesthetics (Flint 2006). In the same study, survey respondents considered the concern for personal safety, due to falling trees, as the SBB outbreak's primary impact. Changing forest aesthetics and increased hazard may have caused people on the Kenai Peninsula to actively avoid forest stands affected by the 1990's SBB outbreak, reducing the chance of small wildfires.

The effects of wildfire suppression classification on the probability both large wildfires and small wildfires were often not statistically signficant. When effects were significant, a critical or full wildfire suppression classification increased the probability of both size classes of wildfires. This is intuitive for small wildfires, because lands designated for wildfire suppression are close to people. Once ignited, these fires remain small because they are more easily suppressed close to roads. However, one would expect that a full or critical fire suppression classification would reduce proability of large wildfire. One plausible explanation is that wildfires were actively suppressed regardless of suppression classification on the Kenai Peninsula. For example, in 2005 15 lightning-caused wildfires ignited in the Kenai National Wildlife Refuge. All but two were suppressed despite the fact that six occured on lands designated for limited suppression and five in wilderness (Morton et al. 2006). The greater number of ignitions in critical and full supression areas, due to humans, may outweigh the increased effectiveness of suppression closer to roads, increasing the probability of large wildfire as compared to more remote areas.

Population density on the Kenai Peninsula is about three times greater than the state average, likely accounting for the use of suppression regardless of classification and ignition source (United States Census Bureau 2010). However, the exclusion of natural-caused wildfire, as a result of suppression, likely increases the proportion of late-successional spruce stands on the landscape, heightening the risk of future large wildfires (Chapin et al. 2003). Our results suggest that the build-up of surface fuels associated with the 1990's SBB outbreak may further amplify this risk. One potential solution is to strategically develop wildfire-suppression policies and fuel-reduction treatments that would allow natural-caused wildfire to burn while still protecting life and property, thereby lowering the chance of a future catastrophic event.

2.5.3 Limitations and Uncertainties

In all 100 of the analyses using the large wildfire, tests for spatial autocorrelation on model residuals were significant ($p < 0.01$) at the 1 km resolution of the study. This is consistent with findings from other bark beetle-wildfire interaction studies (e.g. Kulakowski and Veblen 2007). Spatial autocorrelation presents challenges in using regression approaches to model natural disturance events, such as wildfire, due to their spatial nature and relative rarity on the landscape. This inherent limitation due to spatial dependency calls attention to the need for developing regression models that can accurately estimate the probability of rare events while accounting for the spatial nature of those events. Further, it highlights the utility of integrating multiple scientific approaches including simulation modeling, large-scale experiments, and the adaptive management of ecosystems to understand complex and spatially dependent proccesses.

2.6 Conclusion

Climate change is causing natural disturbance regimes in many systems to increasingly diverge from historical ranges of variation (Flannigan et al. 2009, Turner 2010, Westerling et al. 2006). Due to their importance in shaping successional trajectories and fostering ecosystem heterogeneity, better understanding and accounting for changing natural disturbances is likely integral to effective ecosystem management (Swanson and Chapin 2009). While climate is a critical driver of natural disturbance, additional factors, such as linked disturbance interactions may also influence their characteristics in important ways (Simard et al. 2011). However, as our study suggests, the nature and magnitude of linked disturbance interactions are dynamic, likely to be dependent on drivers specific to the system in which they occur, and may vary as those controlling drivers change over time. Further, the nature of linked disturbance interactions may not be soley contingent on the occurrence of one natural disturbance influencing the other. Instead, characteristics of the initial disturbance, in this case, outbreak length, can play an important role. Differentiating between the effects on wildfire probability attributable to outbreak occurrence versus those attributable to outbreak length may help to develop more effective ecosystem management strategies, such as targeting surface-fuels reduction treatments, and deserve further attention.

Contrasting with research conducted in other systems, as well as work on *historical* bark beetle-wildfire interactions on the Kenai Peninsula, our results indicate a strong positive relationship between the occurrence of 1990's SBB outbreak, the length of the outbreak in a given area, and the subsequent probability of large wildfire. The use of cross-system comparisons allowed us to identify potential drivers that may explain the contrasting results of our study as compared to other work.

In general, however, the relationships between system-specific controlling drivers and the nature and magnitude of linked disturbance interactions are still poorly understood. Examples of drivers from this study that deserve further attention include climate warming, surface fuel loads, and humans. Research is needed to identify common drivers that determine the magnitude of linked disturbance interactions across a number of systems and to characterize the dynamic nature of those relationships. For example, could increasing temperatures begin to initiate future bark beetle-wildfire interactions in other systems? For systems where the relationship between increasing temperatures and bark beetle-wildfire interactions exists, is the magnitude of bark beetle-wildfire interactions incrementally related to warming temperatures, or is there a temperature threshold that, when crossed, linked disturbance interactions "turn on"?

Based on results from the western Kenai Peninsula, the effects of warming temperature on the probability of large wildfire in the boreal forest may be further amplified when in interaction with SBB outbreaks, at least partially due to the outbreaks leading to increased surface fuel loads and amplifying the effects of warming temperatures. However, the reasons why surface fuel loads increased on the Kenai Peninsula, and not in other bark beetle-affected systems (i.e. the Rocky Mountains), remain unclear. Continued work is needed to better understand the determinants of surface-fuel dynamics on the Kenai Peninsula and whether one could expect increasing fuel loads across the boreal system, following SBB outbreaks. Further, we need to better understand how SBB outbreak influences subsequent climate conditions in affected forest stands. Finally, improved simulation modeling is needed to project how natural disturbances, particularly wildfire and SBB outbreaks, are likely to respond, and contribute, to changing climate, social dynamics, and vegetative conditions across the boreal forest. Such information is critical to determine the potential for, and magnitude of, linked disturbance interactions over large spatial scales. This will help us more comprehensively determine the extent to which natural disturbances in the boreal forest are likely to change and inform more effective strategies to manage the ecological implications of those changes.

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Table 2.1. Effect of SBB outbreak occurrence (OOA) on the probability of large wildfire. Final results of rare event logistic regression with replication (RELRR), showing the percent of analyses in which variables were significant, the average logistic coefficient, the corresponding standard error (S.E.), significance, and the odds ratio. Variables not statistically significant are listed below the table.

Variable	Percent	Coefficient	S.E.	Significance	Odds Ratio
SBB Outbreak	100	1.54	0.12	<0.01	4.66
P-PET(mm)	100	-0.02	0.003	<0.01	0.98
Canopy Cover(%)	96	0.004	0.002	<0.05	1.00
Conifer or grass/shrubland	100	1.86	0.21	<0.01	6.42
Road Distance(km)	100	0.04	0.01	<0.01	1.04
Fire Suppression	100	0.48	0.14	<0.01	1.62
North Aspect	100	0.90	0.11	<0.01	2.46
South Aspect	100	0.56	0.14	<0.01	1.76
Constant	100	-7.18	0.28	<0.01	0.001
Variables not statistically significant: Past Fire History					

Table 2.2 Effect of SBB outbreak length (OLA) on the probability of large wildfire. Final results of rare event logistic regression with replication (RELRR) showing the percent of analyses in which variables were significant, the average logistic coefficient, the corresponding standard error (S.E.), significance, and the odds ratio. Variables not statistically significant are listed below the table.

Variable	Count (%)	Estimate	S.E.	Significance	Odds Ratio
SBB Outbreak Length(Index)	100	2.55	0.13	<0.001	12.81
P-PET(mm)	100	-0.02	0.003	<0.001	0.98
Canopy Cover(%)	62	0.004	0.002	<0.05	1.004
Conifer or grass/shrubland	100	1.75	0.22	<0.001	5.75
Road Distance(km)	100	0.02	0.01	<0.001	1.02
Fire Suppression	2	0.30	0.14	<0.05	1.35
North Aspect	100	0.80	0.12	<0.001	2.23
South Aspect	100	0.58	0.15	<0.001	1.79
Constant	100	-6.73	0.26	<0.001	0.001

Variables not statistically significant: Past Fire History

Table 2.3. Effect of SBB outbreak occurrence (OOA) on the probability of small wildfires. Final results of rare event logistic regression with replication (RELRR) showing the percent of analyses in which variables were significant, the average logistic coefficient, the corresponding standard error (S.E.), significance, and the odds ratio. Variables not statistically significant are listed below the table.

Variable	Percent	Coefficient	S.E.	Significance	Odds Ratio
SBB Outbreak	48	-0.34	0.14	<0.05	0.71
P-PET(mm)	100	-0.03	0.005	<0.001	0.97
Canopy Cover(%)	32	-0.004	0.002	<0.05	0.996
Past-fire	100	-0.64	0.17	<0.001	0.53
Road Distance(km)	100	-0.31	0.03	<0.001	0.73
Fire Suppression	28	0.43	0.20	<0.05	1.54
South Aspect	92	0.42	0.15	<0.01	1.52
Constant	100	-3.15	0.19	<0.001	0.04

Variables not statistically significant: Conifer/Non-Forest Cover, North Aspect

Table 2.4. Effect of SBB outbreak length (OLA) on the probability of small wildfires. Final results of rare event logistic regression with replication showing the percent of analyses in which variables were significant, the average logistic coefficient, the corresponding standard error (S.E.), significance, and the odds ratio. Variables not statistically significant are listed below the table.

Variable	Percent	Coefficient	S.E.	Significance	Odds Ratio
SBB Outbreak Length(Index)	20	-0.45	0.22	<0.05	0.64
P-PET(mm)	100	-0.03	0.005	<0.001	0.97
Canopy Cover(%)	38	-0.004	0.002	<0.05	0.996
Past-fire	100	-0.60	0.17	<0.01	0.55
Road Distance(km)	100	-0.31	0.03	<0.001	0.73
Fire Suppression	14	0.42	0.20	<0.05	1.52
South Aspect	92	0.40	0.15	<0.05	1.49
Constant	100	-3.17	0.19	<0.001	0.04

Variables not statistically significant: Conifer/Non-Forest Cover, North Aspect

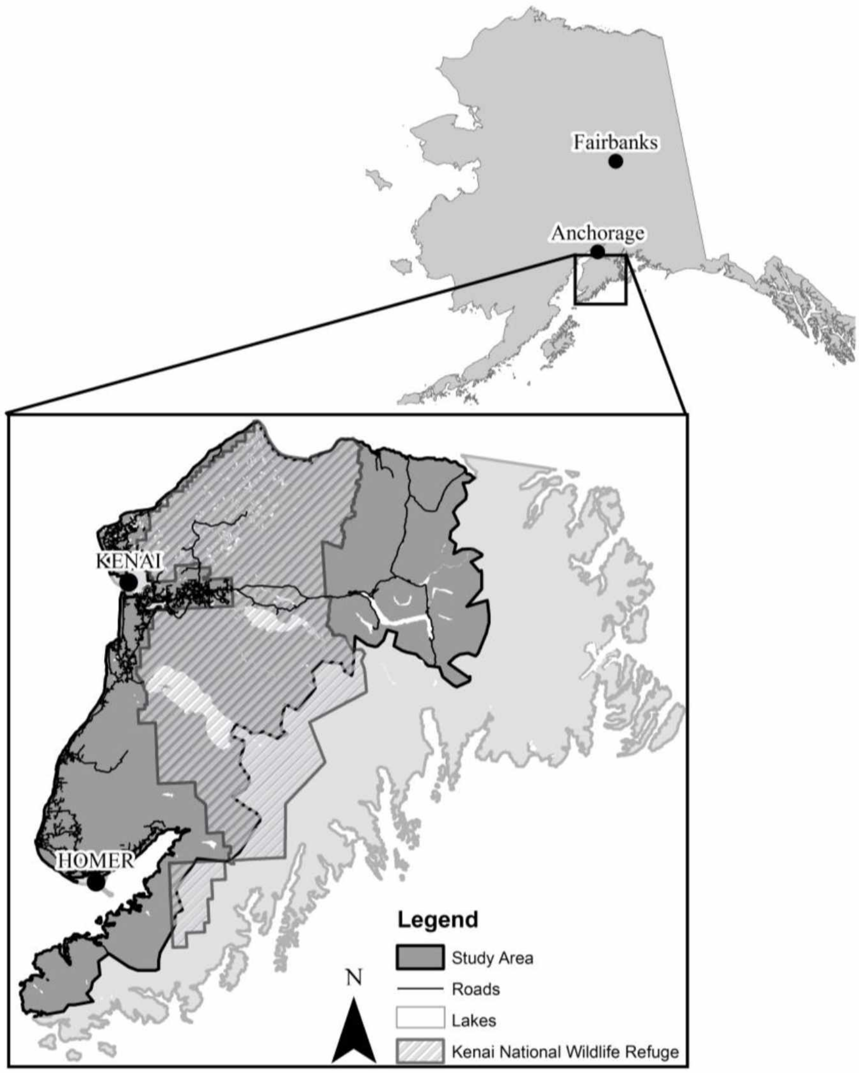

Figure 2.1. Map of the study area on the Kenai Peninsula in south-central Alaska depicting the road system and public land ownership that determines human access to forest stands on the Kenai Peninsula and the Kenai National Wildlife Refuge.

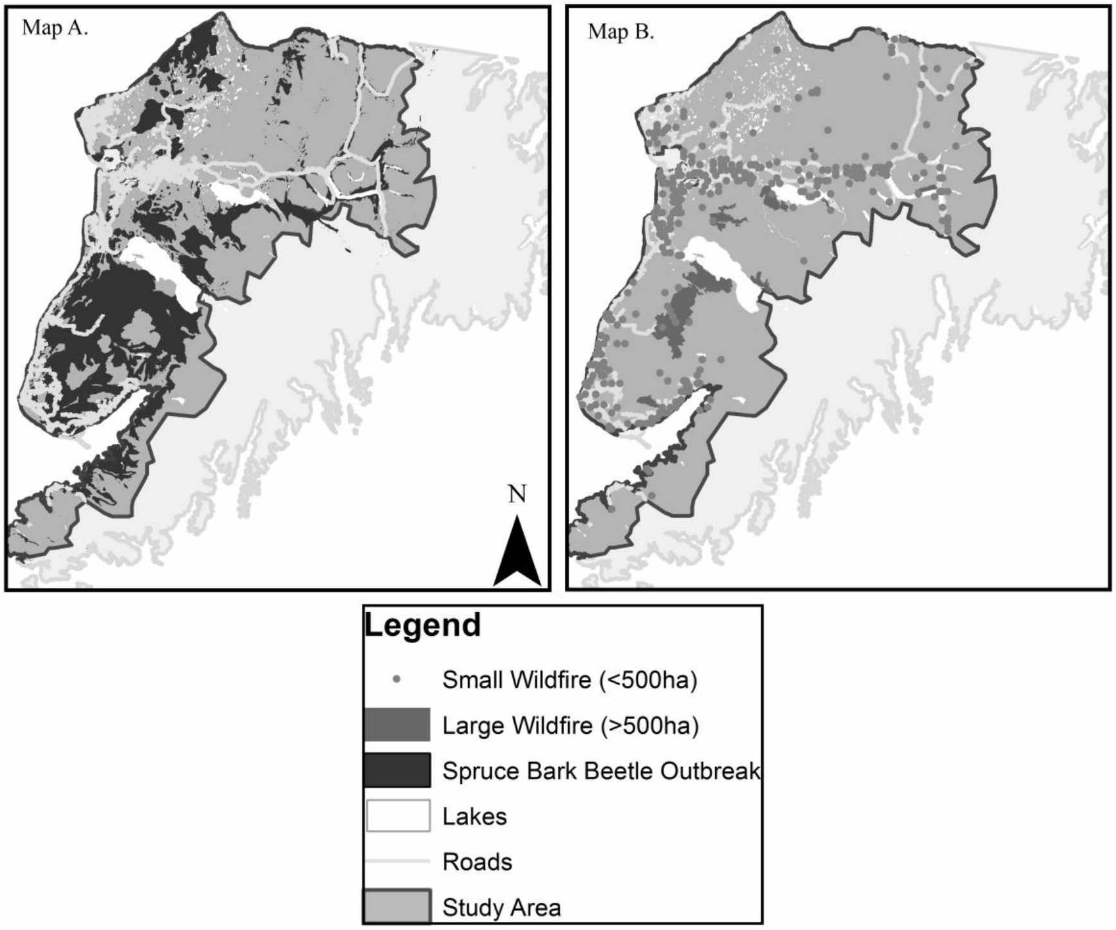

Figure 2.2. Map depicting the occurrence of wildfires and SBB outbreak on the Kenai Peninsula. Map A shows the extent of the spruce bark beetle outbreak from 1989-2000. Map B shows the perimeters of large wildfires (>500 ha) and the point of origin of small wildfires (<500 ha) between 2001 and 2009.

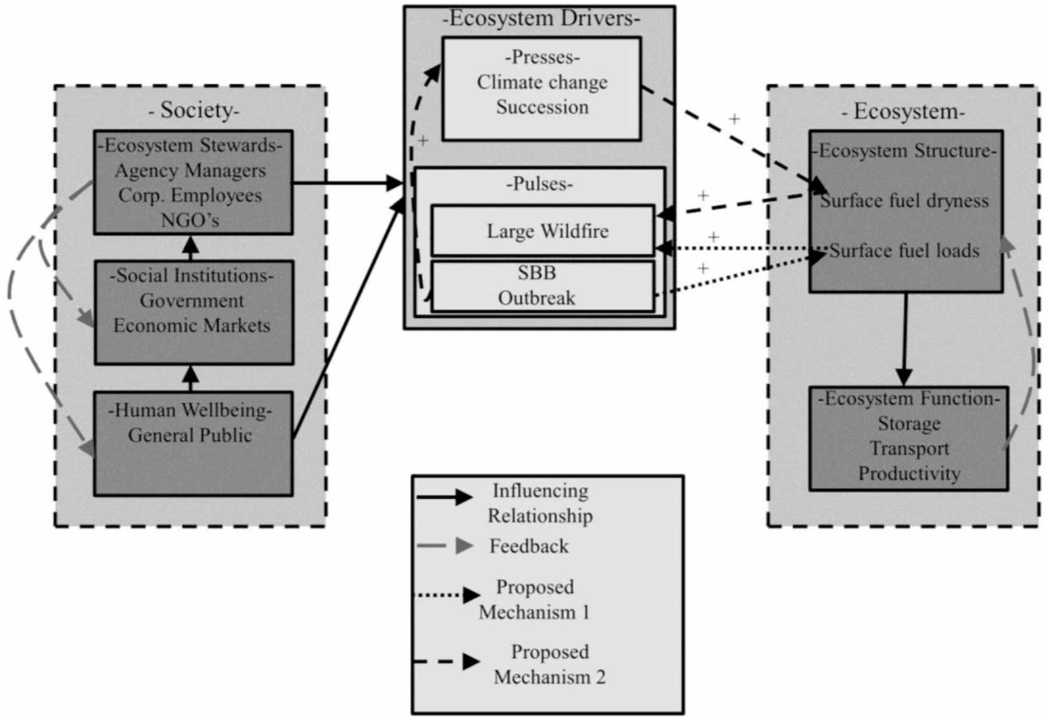

Figure 2.3. Conceptual framework depicting the relationship between SBB outbreak and subsequent large wildfire on the western Kenai Peninsula, AK. Also included are proposed mechanisms for the effects of SBB outbreak on large wildfire. In proposed mechanism 1, SBB outbreak leads to an increase in surface fuel loads which increases the probability of subsequent large wildfire activity. In proposed mechanism 2, SBB outbreak further amplifies already occurring warming trends in the study area. This causes fuels to be drier, increasing the subsequent large wildfire probability.

Chapter 3

The Effects of a Spruce Bark Beetle Outbreak and Wildfires on Property Values in the Wildland-Urban Interface of South-central, Alaska, USA[1]

3.1 Abstract

Climate warming is causing the frequency, extent, and severity of natural disturbances to increase. To develop innovative approaches for mitigating the potential negative social consequences of such increases, research is needed investigating how people perceive and respond to natural disturbance. This study uses spatial econometric techniques in a hedonic pricing framework to estimate how wildfires and a spruce bark beetle (*Dendroctonus rufipennis*) outbreak affect assessed property values on the Kenai Peninsula of south-central Alaska in 2001 and 2010. We find that large wildfires and the spruce bark beetle outbreak increase property values while small wildfires decrease property values. These findings suggest that homeowners may form complex viewpoints, weighing enhancements to environmental amenities with negative consequences that stem from the occurrence of natural disturbance.

3.2 Introduction

Many people in the western United States choose to live in the wildland-urban interface (WUI), semi-rural areas with at least six homes per square km interspersed among forests, shrublands or grasslands (Radeloff et al. 2005; Stewart et al. 2007). Due to warming trends, the frequency, extent, and severity of natural disturbances that occur

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in the WUI, such as wildfire and bark beetle outbreaks, have increased over recent decades (Balshi et al. 2008; Flannigan et al. 2009; Littell et al. 2009; Raffa et al. 2008; Westerling et al. 2006; Westerling et al. 2011). As bark beetles and wildfire respond to a warming climate, effective management approaches are needed to balance the integral ecological role natural disturbances play with the protection of life and property (Chapin et al. 2003; Donovan et al. 2007; Gill et al. 2013). The success of such approaches is likely contingent upon developing a more rigorous understanding of how people living in the WUI perceive and respond to different natural disturbances (Steelman et al. 2004; Sturtevant & Jakes 2008). In this paper we estimate a hedonic pricing model to quantify the economic impacts of a massive spruce bark beetle (*Dendroctonus rufipennis*) (SBB) outbreak and wildfires on assessed property values in the WUI of south-central Alaska.

Between 1970 and 2000, the WUI in the United States expanded by over 50 percent. Approximately 65 percent of the WUI is located in areas where most wildfires burn at high intensity and are difficult to suppress (Theobald & Romme 2007). Federal agencies currently spend over 2.5 billion U.S. dollars annually to suppress wildfires (Weeks 2012). The economic costs of managing bark beetle outbreaks are less clear. There is increasing pressure on agencies to reduce expenditures on the management of natural disturbances, particularly wildfire suppression, while still protecting homes and people in the WUI (Calkin et al. 2005).

Managers are experimenting with several alternative approaches to more cost effectively mediate human-natural disturbance interactions and produce optimal outcomes (Brummel et al. 2010). One example is an effort to proactively engage homeowners in wildfire preparedness through the Firewise Communities program (Kyle et al. 2010). These collaborative projects focus on education and outreach, teaching people the value of creating defensible space around their homes and using fire-resistant building materials in construction. However, convincing homeowners to invest time and money in programs like Firewise Communities is likely contingent on the extent to which people are motivated by diminished environmental amenities (i.e. ecosystem services; human benefits derived from ecosystems; Daily et al. 1997) or a perceived risk of personal harm that can result from natural disturbances (Bright & Burtz 2006).

Yet, homeowners do not always associate the occurrence of natural disturbances with negative consequences that would motivate action to mitigate impacts from future disturbance events. Instead, homeowners often perceive natural disturbance in complex ways. These viewpoints emerge from weighing the cost of diminished environmental amenities and perceived personal risk, caused by natural disturbances, with the benefits of the amenities that disturbances may enhance (Donovan et al. 2007). For example, insect outbreaks cause forest mortality that is generally viewed negatively but also can shift forest composition, an appealing outcome in some geographic locations (Holmes et al. 2006).

Further, the way homeowners evaluate the consequences of one natural disturbance may be influenced by other natural disturbances that co-occur (Berg & Anderson 2006). For example, in some systems, bark beetle outbreaks and wildfire can be interrelated, with one natural disturbance affecting the probability that the other occurs, as well as shaping the consequences of the other, when it does occur (Bebi et al. 2003; Hicke et al. 2012; Simard et al. 2011). Research suggests that the SBB outbreak in south-central Alaska has increased the probability of subsequent large wildfire (Chapter 2). How homeowners in the WUI of south-central Alaska perceive the risk for future wildfire is likely shaped by characteristics of the surrounding system, like whether a SBB outbreak has occurred or not (Flint 2006). Management strategies that more effectively mediate human-natural disturbance interactions in the WUI must account for their contingent or interlinked nature (Venn & Calkin 2011), such as the confounding influence of multiple disturbances.

This study empirically investigates the effects of wildfires and a massive SBB outbreak on assessed property values in the WUI of south-central Alaska. Specifically, we evaluate how wildfires and the SBB outbreak influence property values. Past studies have looked at the effects of wildfire and insect outbreaks on property values independently. However, our study is unique because we account for both types of natural disturbance simultaneously. We find that, when statistically significant, the SBB outbreak and wildfires >3.3 ha have a positive influence on assessed property values.

Secondly, we determine whether the relationships between natural disturbances and assessed property values vary with distance from the property center and change over time since the disturbances occurred. Including spatial and temporal dynamics provides a more comprehensive perspective of how homeowners perceive the SBB outbreak and wildfires. We find that the effects of the SBB outbreak on assessed property values are positive when located between 0.1 km and 1.0 km from property center and the magnitude of effects increase with time since the disturbance occurred. Wildfires > 3.3 ha have a positive effect on assessed property values when located within 0.1 km of property center. These effects are also magnified over time. Wildfires < 3.3 ha have a negative effect on assessed property values when located within 0.1 km of property center and a positive effect when located between 0.1 km and 0.5 km from property center. The effects of small wildfires diminish over time, regardless of distance from property center.

We also model spatial interactions inherent to property values. Failing to account for spatial autoregression and spatial autocorrelation can lead to biased and inefficient coefficient estimates. In our analysis we estimate the OLS, the spatial lag, the spatial error, and the spatial mixed models. Additionally, we present formal test statistics for choosing between them. We find that spatial econometric models are statistically superior to the OLS model, highlighting their importance in this context.

In section two we discuss contextual background including the ecological roles of wildfires and SBB outbreaks and their effects on property values. Section three describes the dataset used in our models. Section four explains the modeling methodology. Section five presents results and section six concludes our study.

3.3 Contextual Background

3.3.1 The Ecological Role of Wildfire and Bark Beetle Outbreaks

Natural disturbances, such as wildfire and bark beetle outbreaks, are integral to the function of many ecosystems. Acting over short time frames, wildfire and bark beetle outbreaks shape system states and re-direct ecological trajectories (Turner 2010). They can also foster increased landscape heterogeneity, an important structural component of ecosystems (Turner et al. 1998; Turner et al. 2003). As a result, wildfires and bark beetle outbreaks often play a key role in determining the quality and quantity of environmental amenities provided for human use (Turner et al. 2012). Environmental amenities affected by wildfire and bark beetle outbreaks include carbon storage, timber production, wildlife habitat, and forest aesthetics (Balshi et al. 2009; Chapin et al. 2003; Cyr et al. 2009; Gallant et al. 2003; Hammer et al. 2007; Hunt & Haider 2004; Rupp et al. 2006).

Wildfire and bark beetles respond strongly to climate drivers, particularly temperature increases. Both natural disturbances are projected to increase in frequency, severity, and extent as a result of anthropogenic climate change. For example, across the North American boreal forest, studies estimate that by the end of the 21st century, annual area burned by wildfire is likely to increase by 74 to 118% (Balshi et al. 2008; Flannigan et al. 2005). Significant increases in the number of large wildfires are projected in the Rocky Mountain West as well (Westerling et al. 2006; Westerling et al. 2011).

Similarly, bark beetle outbreaks are now occurring in forests at more northerly latitudes and at higher elevations than previously recorded (Raffa et al. 2008). Warming temperatures accelerate the rate at which bark beetles can reproduce, increasing their population numbers and allowing the insects to overwhelm tree defenses (Hansen et al. 2001). A number of current outbreaks are some of the most severe ever recorded. Models suggest that the expansion of bark beetle outbreaks will continue through the 21st century (Bentz et al. 2010). The positive response of wildfires and bark beetles to climate warming is likely to have important implications for people, particularly those living in the WUI. Increases in natural disturbance will diminish the quality and quantity of some environmental amenities while enhancing others (Turner et al. 2012).

3.3.2 Wildfire Effects on Property Values and Spatial Interactions

To our knowledge, six studies have been conducted to evaluate the effects of wildfire on property values using a hedonic pricing framework, none of which evaluate the effects of fire on property values in the boreal forest or have accounted for the potentially confounding effects of bark beetle outbreak. In the summer of 1994, a series of large wildfires burned over 73,000 ha of forest in Chelan County, Washington. Suppression costs exceeded 69 million U.S. dollars and there was significant loss of personal property. Results of a hedonic model suggest that proximity to wildfires negatively impact property values in the county (Huggett 2003). This indicates that the diminished environmental amenities or an increase in perceived risk of future wildfire outweigh any enhancements in amenities caused by these wildfires. However, the negative effects of the 1994 wildfires on property values only lasted for 6 to 12 months.

The findings of this study highlight the importance of temporal dynamics in determining peoples' perceptions of, and responses to, natural disturbance events.

The 1996 Buffalo Creek fire burned over 4,800 ha in Colorado. The wildfire began in a national forest and eventually destroyed ten homes in the city of Buffalo. A hedonic pricing model of home sales pre- and post-fire in the nearby (2 km) but unaffected town of Pine, from 1993 to 2001, indicates that a nearby wildfire reduces home prices by an average of approximately $17,000 dollars, or 15% (Loomis 2004).

In 2002, the fire department of Colorado Springs, Colorado assessed wildfire risk around 35,000 WUI homes and made their findings public. A study was conducted to evaluate how environmental amenities and characteristics determining wildfire risk, such as vegetation density and dangerous topography, influence home sale prices before (1998-2001) and after (2002-2004) the release of the fire-risk map (Donovan et al. 2007). The results suggest that increased awareness of wildfire risk has a negative, but fleeting effect on home sale prices. The selling price of a representative home decreased by $40,000 after the release of the wildfire risk map. Yet, the individual characteristics that determine wildfire risk influence sale prices differently. For example, the relationship between dangerous topography around homes and their selling prices do not change. This suggests that the benefits of living on a ridge outweigh the negative costs associated with increased awareness of wildfire risk. Conversely, homes constructed with wood roofs or wood siding (large contributors to wildfire risk) have either a positive effect or no-effect on home sale prices, before the release of the risk map, and a negative effect after its release. This indicates that the aesthetic value of wood homes is overshadowed by the greater awareness of wildfire risk. These results illustrate ways in which homeowners form complex viewpoints by weighing the negative impacts of wildfire risk with the benefit of environmental amenities available to people living in wildfire-prone areas.

The importance of spatial econometrics in hedonic property-value studies has been demonstrated[i]. Not accounting for spatial spillovers can lead to biased coefficient estimates. In the fire-risk map analysis, Donovan et al. (2007) provide formal diagnostics to choose between different model specifications and find support for the joint spatial lag/spatial error model (spatial mixed model). The authors further estimate economically significant absolute percentage of bias of the OLS marginal effects. The average bias ranges from 37% to 167% in their four models.

A small WUI area near Los Angeles, California experienced five wildfires during the 1990's. Using data from 1989 and 2003, Mueller et al. (2009) identified homes within 2.8 km of at least one wildfire and quantified the effects of multiple wildfires on home sale prices. Findings indicate that wildfires have a negative effect on home sale prices. However, multiple wildfires influence sale prices differently. The first wildfire decreases sale prices by 10%, or by an average of $14,744. The second wildfire decreases sale prices by 23%, or $34,453. By considering the effects of multiple wildfires, this study is more comprehensive than those that include a single natural disturbance event. Using the same dataset, Mueller & Loomis (2008) show that spatial error was present in these data.

However, controlling for the spatial dependence in a variety of specifications did not greatly improve coefficient estimates over OLS.

Past studies described in this literature review have evaluated the influence of one or a few wildfires on property values. However, in wildfire prone areas, the landscape is a patchwork of many fire scars that accumulate over time. Stetler et al. (2010) looked at the effects of 256 wildfires and a number of environmental amenities on home sale prices from 1996 to 2007 in northwestern Montana. The authors included the distance of homes from past wildfire, whether there was a view of a past wildfire, and time since the wildfire occurred. They find that proximity to past wildfires negatively influences the selling price. However, homes with a view of where the wildfire burned have lower selling prices, and property values take longer to recover than those without a view of the wildfire.

3.3.3 Insect Outbreak Effects on Property Values and Spatial Interactions

Two studies have evaluated the effects of insect outbreaks on property values. The hemlock woolly adelgid (*Adelges tsuga*) was introduced by accident to the forests of Virginia in the early 1950's and spread throughout the northeastern United States. The insects cause mortality to a variety of hemlock species. Using records from 1992 to 2002 in Sparta, New Jersey, Holmes et al. (2006) quantified how hemlock woolly adelgid outbreak severity influences home sale prices. The authors incorporated additional variables such as land use, proximity to water, home characteristics, and locational characteristics. They find that moderately declining stands of hemlock, as a result of the insects, have a negative influence on home sale prices. However, severely declining stands have no influence. Dead hemlock stands, caused by insect outbreak, positively influence home sale prices. The authors speculate that an increased amount of light reaches the forest floor following severe insect-caused hemlock mortality. Increased light may stimulate the growth of other deciduous tree species. In the model, deciduous forest cover is associated with increases in property values. An expansion of deciduous tree cover likely outweighs any diminished environmental amenities from lost hemlock stands.

The authors also estimate spatial lag and spatial error models. Finding both significant, they present a final spatial mixed model. In this specification, the spatial error remains significant, while the spatial lag does not. However, the authors do not provide a formal diagnostic for assessing performance among the different spatial specifications.

Between 1996 and 2010, a Mountain Pine Beetle (MPB) (*Dendroctonus ponderosae*) outbreak infested 769,000 hectares of forest in Colorado. A study was conducted in the WUI of Grand County, to determine how the number of trees killed by MPB within 0.1, 0.5, and 1.0 km of homes affected their sale price using data from 1995 to 2006 (Price et al. 2010). Home sale prices decline by $648, $43, and $17 for each tree killed within the 0.1, 0.5, and 1 km radii, respectively. These results indicate that the negative effects of mountain pine beetle damage decrease with distance from the home.

The authors also estimate a spatial lag model and find the spatial lag coefficient to be highly significant in all three models. It appears that the effects of trees killed by MPB on home sale prices spill over to influence the selling price of neighbors' homes. However, the study does not account for spatial autocorrelation. In our study, we present formal test statistics for choosing between the spatial lag, spatial error and spatial mixed models. This helps us to reveal the mechanisms responsible for spatial processes.

3.4 Study Area and Data Sources

Our study area is the WUI of the Kenai Peninsula in south-central Alaska (Figure 3.1), focused primarily on the western portion of the peninsula. The western Kenai Peninsula extends from Cook Inlet on the west, to Prince Williams Sound on the east, and is located south of Anchorage, Alaska. Mean annual precipitation varies from 369 mm in the northwestern portion of Kenai Peninsula to 650 mm at the southern extent (1970-2000) (Western Regional Climate Center 2012). Average annual temperature is approximately 1℃ (Sherriff et al. 2011). Forests of the western Kenai are classified as boreal transition. Lutz spruce (*Picea lutzii*) and sitka spruce (*Picea sitchensis*) are located along the coast lines. Interior forest stands comprise white spruce (*Picea glauca*) and resin birch (*Betula neoalaskana*). White spruce stands of the western Kenai Peninsula have been host to an average of 66 wildfires per year that burned over 60,000 ha since 1990 (Figure 3.2), including the 2007 Caribou Hills wildfire that destroyed 88 homes and cabins and 109 outbuildings (Kenai Peninsula Borough 2011). A massive SBB outbreak began in 1989, affecting over 400,000 ha, until it petered out in the early 2000's (Figure 3.3). Since then, isolated SBB outbreaks have occurred.

The Kenai Peninsula Borough is more densely populated than much of the rest of Alaska. According to the 2010 United States Census, 55,400 people reside within the borough, and population has grown by 11.5% since 2000. Per capita annual income is $29,127 (2010 U.S. real dollars). The economy in the Kenai Peninsula Borough is one of the most diverse in the state. Oil and gas exploration play an important role, as does sales and services, construction, and tourism (Kenai Peninsula Borough 2010). There are five incorporated cities in the borough including, Homer, Kenai, Seldovia, Seward, and Soldotna, and a number of unincorporated towns. Around the road system, a pronounced WUI has developed, particularly on the western side of the peninsula. As of 2011, there were approximately 10 properties per square km in the WUI (Kenai Peninsula Borough 2012).

This paper quantifies the effects of wildfires and the 1990's SBB outbreak on assessed property values in 2001 and 2010 for single household residences in the WUI of the Kenai Peninsula. We further include a suite of spatial, environmental, geographic, and property characteristics in our analysis. Assessed property values and property characteristics are publically available from the Kenai Peninsula Borough (Kenai Peninsula Borough 2012).

As of 2010, there were over 60,000 identified properties in the Kenai Peninsula Borough. However, we limit our sample in three ways. First, we only include private, single dwelling properties (i.e. one home), located in the community wildfire protection plan zone (CWPP), or areas with a sufficient density of homes on the Kenai Peninsula for the borough to prioritize wildfire suppression. For this analysis, we consider the CWPP to delimit the WUI. The WUI does not include urban settings; hence we exclude any properties that were located within the limits of incorporated cities on the Kenai Peninsula. Further, we only include properties with at least one bathroom and one bedroom, as some homes in Alaska still have outhouses. Finally, we only include properties for which assessed land and home values were available for both 2001 and 2010. This yields 4,398 properties for analysis.

Alaska is a non-disclosure state. Thus, the selling prices of properties are not publically available. We define a property's value as the logarithm of the sum of annual assessed land value and annual assessed home value. Assessments were conducted by the Kenai Peninsula Borough Assessing Department to calculate property taxes owed. Title 29, Section 45.110 of the Alaska State Constitution mandates that property in Alaska must be regularly assessed, and the assessed value must be equivalent to the property's fair market value. In other words, property must be valued at what the owner views as fair on the real estate market. The Kenai Peninsula Borough Assessing Department evaluates their own ability to meet the state's fair market valuation mandate by surveying recent homebuyers. In the Kenai Peninsula Borough, the mean assessed value to sales price ratio ranged from 92 percent in 2006 to 94.5 percent in 2010. While this undervaluation contributes to measurement error, we find no reason to believe that this measurement error is systematically related to the independent variables in our model. We believe our results provide valuable insight into the relationships between the 1990's SBB outbreak, wildfires, and property values.

Perimeters of 33 wildfires > 3.3 ha and the point of origin of 1160 wildfires < 3.3 ha that burned between 1990 and 2010 came from the Alaska Fire Service's Fire History of Alaska Database (Alaska Fire Service 2012). Using historical records, aerial surveys, and remote sensing, the Alaska Fire Service maintains spatially explicit fire perimeter records dating back to 1940 (Kasischke et al. 2002). The U.S. Forest Service and Alaska Department of Natural Resource annually conduct Alaska Forest Health Aerial Surveys to detect and map insect outbreaks throughout much of the state, focusing on areas of high priority and known outbreaks (United States Forest Service & Alaska Department of Natural Resources 2012). Perimeters of the SBB outbreak between 1990 and 2010 in the study area came from these surveys.

We include dummy variables to account for the occurrence of wildfires > 3.3 ha, wildfires < 3.3 ha, and the 1990's SBB outbreak within three distance bands from property center: < 0.1 km, 0.1 km to 0.5 km, and 0.5 km to 1.0 km, matching the distance bands of Price et al. (2010). We also include dummy variables accounting for time since natural disturbances occurred at these different distance bands. The two time intervals in this model accounted for disturbances that occurred within the previous five years of an observation and disturbances that occurred in the previous 6-20 years. Unlike wildfire, SBB outbreaks are not events that take place during an individual season, but may continue over several summers. In this study, we define time since the SBB outbreak as the number of years since the outbreak was initially detected.

Percent upland non-forested (grassland, shrubland and cultivated pasture) and percent forested (coniferous, deciduous, and mixed forest) land cover within a 500 m radius of each property's center were calculated using data from the 2001 National Land Cover Database (Homer et al. 2004). Vegetation categories not in this analysis include wetlands, developed areas, and barren soil. Developed by the United States Geological Survey's Multi-Resolution Land Characteristics Consortium, the NLCD vegetation classification is comprised of information from circa 2001 Landsat ETM+ satellite imagery. Data on property elevation came from the United States Geological Survey's National Elevation Dataset (Gesch et al. 2002; Gesch 2007).

We included variables such as mean winter (December through February) and summer (June through August) temperature and precipitation between 2000 and 2009 to control for climatic differences across the study area. Gridded CRU TS 3.1 temperature and 3.1.01 precipitation data were downscaled to a 1 km resolution by Scenarios Network for Alaska and Arctic Planning (Jones & Harris 2008; Mitchell & Jones 2005; SNAP 2012).

Several geographic characteristics are included in this analysis: distance to the nearest incorporated city, a dummy representing which incorporated city is nearest, distance from the coast, distance from the nearest inland water body (i.e. lakes and rivers), distance to the nearest primary road, distance to the nearest secondary road, and distance to the nearest school. These were calculated using geo-spatial data provided by the Kenai Peninsula Borough Geographic Information Department[ii]. While assessing property values, the Kenai Peninsula Borough Assessing Department records details on structure and property characteristics. Our analysis incorporates property size, home finished square footage, the number of stories, the number of bedrooms, the number of bathrooms, and home age.

3.5 Empirical Model

Proposed by Rosen (1974), the hedonic pricing framework relates the value of a home to the home's individual characteristics:

$$(1) \quad Home\ Value = f(E, G, D),$$

where E represents environmental, G geographic and D dwelling and other property characteristics. Following past research that demonstrates the importance of spatial processes in hedonic pricing analyses (Donovan et al. 2007; Mueller & Loomis 2008; Ham et al. 2012), central to this analysis is the maximum likelihood estimation of the spatial mixed model with the spatial lag and spatial error terms. Our model estimates the log-transformed assessed value of property i in year t, P_{it}:

$$(2)\ P_{it} = \rho \sum_{i \neq j} \omega_{ij} P_{jt} + \beta_0 + \beta_1 Z_{it} + \beta_2 E_i + \beta_3 G_i + \beta_4 D_i + \gamma Yr2010_t + u_{it},$$

where

$$(3)\ u_{it} = \lambda \sum_{i \neq j} \omega_{ij} u_{jt} + \varepsilon_{it}$$

The spatial lag, $\sum_{i \neq j} \omega_{ij} P_{jt}$, is the weighted average of the other properties' assessed values. Weights are based on the inverse distance between properties in the sample[iii]. The spatial lag coefficient, ρ, provides insight into strategic interactions between properties. In other words, ρ describes how the assessed value of one property is influenced by the assessed values of other neighboring properties. For example, if neighboring properties have a high value, a particularly strong tax base may lead to infrastructure improvements close to homes and higher quality schools, increasing both demand for properties in that area and their values.

The spatial error, $\sum_{i \neq j} \omega_{ij} u_{jt}$, is the weighted average of other observations' error terms, using the same weights as the spatial lag. The spatial error coefficient, λ, is not interpretable in terms of strategic interactions, but does provide evidence of either spatial similarity ($\lambda > 0$) or dissimilarity ($\lambda<0$) between the properties located near one another[iv].

The natural disturbance variables in Z_{it} vary across properties and over time. These include wildfire > 3.3 ha, wildfire < 3.3 ha, and SBB outbreak dummy variables for three different distance bands. For the statistically significant disturbance distance bands we then separately estimate short-term (1-5 years) and long-term (6-20 years) effects. Including all eighteen natural disturbance distance and time dummies at once causes multicollinearity problems.

Environmental characteristics, E_i, vary across properties but remain constant over time. These include summer and winter temperature and precipitation, percent area forested, percent area non forested, and elevation. Time invariant geographic variables, G_i, include incorporated city fixed effects and distances to the nearest incorporated city, school, primary road, secondary road, section of coast and inland water body. Dwelling and property characteristics, D_i, also constant over time, include property size, finished home square footage, home age, number of bedrooms and bathrooms, and number of stories. The models also include a dummy variable for year 2010, $Yr2010_t$, and an i.i.d. random error term, ε_{it}.

To provide a baseline, we first assume that both the spatial lag and spatial error coefficients equal zero and estimate the OLS model. Next, we estimate the spatial lag and spatial error models separately, allowing each to sequentially take on non-zero values. Finally we estimate the full spatial mixed model.

3.6 Results

We conduct a spatial econometric analysis to better understand how wildfires, a massive SBB outbreak, and other property characteristics influence assessed property values in the WUI of south-central Alaska in 2001 and 2010. This section discusses the estimated models that separately include the natural disturbance distance variables and the short- and long-term effects of disturbance. In our analysis, OLS models are always rejected in favor of the spatial mixed models using likelihood-ratio (LR) tests[v]. Thus, we focus our discussion on the spatial mixed models.

3.6.1 Natural Disturbance Distance Variables

Table 3.2 presents the models for assessed property values with the natural disturbance dummy variables at different distance bands. These models provide insight into how the occurrence of the SBB outbreak, wildfires > 3.3 ha, and wildfires < 3.3 ha affect property values. We find that the occurrence of natural disturbances influences assessed property values. However, the direction and magnitude of effects varies by disturbance type and distance from property.

Wildfires > 3.3 ha that occur within 0.1 km of a property increase assessed property values by 18.6%[vi]. Wildfires < 3.3 ha decrease assessed property values by 5.5% when located within 0.1 km of property center and increase property values by 2.4% when located between 0.1 km and 0.5 km of property center. The occurrence of SBB outbreak within 0.1 km to 0.5 km and 0.5 km to 1.0 km of property center increases assessed property value by 3.7% and 2.1%, respectively. With the exception of wildfires < 3.3 ha at close distances, the natural disturbances included in these models have a positive effect on property values. This suggests that the benefits of enhanced environmental amenities associated with wildfires and the SBB outbreak at certain distances outweigh the costs.

In addition to natural disturbance, a number of other environmental amenities influence property values in our analysis. For example, a one percentage-point increase in the percent area that is non-forested upland grassland or shrubland around a home increases property values by 0.1%. Conversely, increasing the percent forest cover by one percentage-point decreases assessed property values by 0.2%. This finding is supported by other studies that find a negative correlation between forest density and property values (Holmes et al. 2006; Kim & Wells 2005). A 1°C increase in average winter temperature decreases assessed property values by 2.3% and a 1 mm increase in average summer precipitation decreases property values by 1.4%.

As expected, a 1% increase in the distance to the nearest incorporated city decreases assessed property values by 0.08%. Increasing distances from both the coast and inland water bodies by 1% decreases assessed property values by 0.03% and 0.08%, respectively. A 1% increase in distance from the nearest secondary road increases property values by 0.02%. Distance from the nearest primary road had a statistically insignificant effect. The effects of property and home characteristics were all intuitive. Homes on larger parcels have higher assessed values. Older homes have lower assessed property values. Homes with more bedrooms and more bathrooms, and larger homes all have higher values.

The spatial lag coefficient, ρ, was positive and significant, providing evidence of spatial interactions between the assessed values of neighboring properties. An increase in neighboring properties' assessed values of 1% increases the assessed property value by 0.94%. This suggests that the factors influencing the assessed value of one property such as natural disturbances, infrastructure development, and school quality will spillover to affect the value of neighboring properties.

3.6.2 Short-term and Long-term Effects

To distinguish between the short-term and long-term effects of natural disturbances on housing prices, we estimate the natural disturbance effects during the first five years and the subsequent sixteen years for the statistically significant distance bands in Table 3.2. Regressions incorporating these short-term and the long-term effects are found in Table 3.3. This form of the regression captures how the effects of wildfires > 3.3 ha, wildfires < 3.3 ha, and SBB outbreak on assessed property values change with time since the disturbances occurred, reflecting ecosystem recovery from disturbance events.

We find that the effects of wildfires > 3.3 ha and SBB outbreak on property values are magnified with time since the disturbance occurred. For example, wildfires > 3.3 ha that burned within 0.1 km of property center in the previous five years have a statistically insignificant effect on assessed property values. However, fires > 3.3 ha that burned within the same distance, but between 6-20 years previously, increase assessed property values by 21.3%. The effects of SBB outbreak between 0.1 km and 1.0 km from property center are also magnified through time, increasing property values by 2.2% and 3% when they occur in the previous five years and in the previous 6-20 years, respectively.

The negative effects of wildfires < 3.3 ha diminish with time. Wildfires < 3.3 ha that occurred within 0.1 km of property center decrease property values by 7.3% in the first five years since their occurrence, and decrease assessed property values by 4.4% after the first five years. Similarly, the positive effects of wildfires < 3.3 ha that burned between 0.1 km and 0.5 km from property center diminish with time. The coefficients of other variables remain largely unchanged with the addition of time effects.

3.7 Conclusion

Past research investigating the effects of wildfire and insect outbreaks on property values have overlooked the potentially confounding influence of co-occurring natural disturbances. Our spatial econometric analysis suggests that wildfires and SBB outbreaks affect assessed property values on the Kenai Peninsula. However, the nature of their influence differs as a function of disturbance type, with distance from property centers, and with time since disturbance occurred. Our most surprising result is that wildfires > 3.3 ha and the SBB outbreak were associated with increases in assessed property values. As expected, though, wildfires < 3.3 ha that burn very close to properties (< 0.1 km) have a negative effect on assessed property values. We offer some potential explanations (Figure 3.4).

One possible explanation for the positive effects of natural disturbances on WUI property values is that the benefits of enhanced environmental amenities, as a result of the SBB outbreak and wildfires > 3.3 ha, outweigh the costs of diminished environmental amenities. For example, before the occurrence of a large natural disturbance, properties located in the WUI of the western Kenai Peninsula are primarily surrounded by relatively dense forest. Following a disturbance, the trees are killed and fall, opening up aesthetically pleasing views of Cook Inlet and the Aleutian Mountain Range beyond. The improved views of the ocean and mountains may outweigh the negative impacts associated with natural disturbances. This hypothesis is further supported by the estimated positive effect of percent non-forested land cover on property values, in ours, as well as other studies (Holmes et al. 2006; Kim & Wells 2005). The magnification over time of these positive effects on property values likely reflects ecological recovery that reduces the less pleasing consequences of disturbance, such as charred biomass, while views remain. This is consistent with forest succession patterns on the Kenai Peninsula.

Secondly, following SBB outbreak or the occurrence of a wildfire > 3.3 ha, homeowners may perceive a decreased risk of future wildfire. For large wildfires this hypothesis is intuitive, as once a large wildfire has burned an area, it is unlikely another will occur for potentially hundreds of years (Berg & Anderson 2006). However, recent research suggests that the SBB outbreak actually increases risk for subsequent wildfire (Chapter 2). Yet, following the SBB outbreak, extensive salvage logging was conducted. It may be that salvage logging fosters a perception of decreased wildfire risk, whether the actual risk is actually reduced or not. The positive effects are also likely magnified over time as people continue to perceive a reduced risk of fire while early successional plants establish and diminish the unpleasant impacts of wildfire or salvage logging on the landscape.

Wildfires < 3.3 ha that burned very close to properties are the only natural disturbance to have a negative effect on assessed property values in this study. We hypothesize these wildfires burn close enough that homeowners are reminded of wildfire risk. However, the wildfires are small enough that they do not kill the majority of vegetation or open up aesthetically pleasing views. Thus, homeowners do not perceive a decreased risk of future wildfire as they would with large wildfires that destroy most vegetation, nor do they benefit from views of the ocean and mountains. The effects diminish with time as these past wildfires slip into the backs of peoples' minds.

In south-central Alaska, our findings could help inform solutions that balance the integral roles wildfires and SBB outbreaks play in the boreal ecosystem with the protection of life and property in an expanding WUI. For example, research in the western United States suggests that targeting fuels reduction treatments to create defensible space around homes in the WUI is a substantially more cost-effective approach than treating all forests affected by bark beetle outbreak (Aronson & Kulakowski 2013). Managers could potentially garner more public support, active involvement, and financial backing to conduct targeted wildfire fuel reduction treatments in the WUI if they design treatments to maximize the improvement of aesthetically pleasing views around homes. Homeowners may be more receptive to explanations of how fuel reduction treatments allow wildfire to burn naturally, while still keeping their homes safe, if they see that such treatments will also increase their property values.

Accounting for spatial interactions provides valuable insight with direct policy application, in addition to ensuring unbiased coefficient estimation. The positive spatial spillovers found in this study could help demonstrate to homeowners that reducing fuel loads around homes not only increases their own property values but also positively affects the property values of their neighbors' homes. Conveying how the benefits of proactively managing human-natural disturbance interactions spill over among properties might help bring neighborhoods together around the issue of protecting their homes, motivate broader public participation, and increase pressure on those resistant to action.

Past research using stated preference techniques to document the perceptions of Kenai Peninsula residents identified a mixed relationship between the 1990's SBB outbreak and property values (Flint 2006). Interviews with residents provided evidence for our emerging views hypothesis. Improved views were considered by some to be a positive outcome of the SBB outbreak. However, in surveys conducted for the same study, 67% of respondents presumed that their property values had decreased as a result of the outbreak. Flint (2006) does not speculate why respondents associated the outbreak with reductions in property values. Participants also expressed concern for personal safety as a result of falling dead trees, an emotional sadness associated with changing natural aesthetics, and a mixed outlook on future wildfire risk, depending on the community sampled. Differences in the results of our study and past work on the Kenai Peninsula highlight the complex and dynamic viewpoints people develop regarding the perceived consequences of natural disturbances.

In general, to create and implement innovative management strategies, we must better understand the mechanisms through which people evaluate the consequences of natural disturbance and the magnitude of their influence (Venn & Calkin 2011). This presents a substantial challenge because perceptions of natural disturbances are likely to vary significantly between geographic locations, over time and, as Flint (2006) demonstrates, between people within a single location. In addition, it has long been shown that revealed preference versus stated preference techniques can yield different views of how the same group of people perceives environmental amenities (Adamowicz et al. 1994; Adamowicz et al. 1997). Yet, both techniques may provide complementary manager-relevant insights into two different dimensions of complex human-perception dynamics (Chasco & Gallo 2012). Continued research is needed to better integrate the results of revealed preference and stated preference studies, determining in what contexts the approaches yield similar results and to what extent the results of each are useful for managing natural disturbance-human interactions in the WUI.

Another important disconnect exists between recent advances in our ecological understanding of natural disturbances, context-specific ecological nuances, and economic valuation. “The reliability of natural science data is generally unquestioned in economic analysis of environmental change. Rarely is an economic study conducted in association with a new piece of scientific research or are site specific current damage estimates obtained” (Spash & Vatn 2006, p. 381). For example, recent ecological research suggests that the occurrence of one form of natural disturbance can actually alter the characteristics of another natural disturbance, and thus its consequences for people, a concept known as linked disturbance interactions (Chapter 2; Donato et al. 2013; Turner 2010; Simard et al. 2011). In other words, models of how wildfires affect property values in the WUI may be incomplete without considering the confounding influence of co-occurring natural disturbances, such as SBB outbreak.

We also need to identify the ecological consequences of natural disturbances that are particularly relevant to human wellbeing (Venn & Calkin 2011). What suites of environmental amenities, important to people, are affected by different types of natural disturbances? How do varying characteristics (e.g. frequency and severity) of those disturbances change the extent to which they affect environmental amenities? Does variation in the extent to which environmental amenities are affected by disturbance influence how people perceive the consequences of that disturbance? Meaningful collaborations between ecologists and economists could help to better assimilate social and ecological complexities into single, more comprehensive forms of analysis that accommodate multifaceted, non-linear interactions and feedbacks between multiple drivers.

One promising approach for assimilating and better understanding the influence of complex social and ecological characteristics is the use of systems dynamics analysis (Meadows 2009). The technique allows researchers to visually map out potential actors, drivers, and feedbacks of a system and quantitatively define the nature and magnitude of their interactions (Ford 1999). This could provide researchers with a framework to conceptualize what is known about how natural disturbances affect ecosystem structure and function, environmental amenities, peoples' perceptions of the consequences of disturbance, and identify where further research is needed. Once a system has been mapped, interactions parameterized, and the model is validated, sensitivity analysis could simulate how changes in key variables will play out through the system. This will help managers identify promising leverage points where intervention may foster improved social and ecological outcomes.

Future research is needed to continue characterizing WUI human-natural disturbance interactions on the Kenai Peninsula, across the North American boreal forest, and more broadly. Using the occurrence of past SBB outbreak and wildfires to encourage support for proactively managing future human-natural disturbance interactions will likely require tailoring the scope and benefits of specific management actions to fit the needs of diverse citizen groups on the Kenai Peninsula. However, this study does highlight promising opportunities for fuels reduction treatments that could let naturally-caused wildfire burn more safely. We also offer ways to incentivize participation and support for those treatments. Some of the hypotheses and management prescriptions presented in this paper are built on characteristics specific to the Kenai Peninsula, Alaska, such as emerging views of mountains and ocean. However, the unique findings of this study also call attention to key generalizable principles. This paper identifies and prioritizes future research needs, based on these principles, which could improve our understanding of complex human-natural disturbance interactions and help us to more effectively manage such interactions in the WUI of many different systems.

3.8 Appendix OLS estimates

VARIABLES	(1) No Disturbance	(2) Large Wildfire	(3) Small Wildfire	(4) SBB	(5) All Disturbance
Large Wildfire [a] <0.1 KM		0.211***			0.227***
		(0.059)			(0.059)
Large Wildfire <0.5 KM		0.190**			0.184**
		(0.092)			(0.090)
Large Wildfire <1.0 KM		0.070*			0.058
		(0.042)			(0.041)
Small Wildfire [b] <0.1 KM			-0.067**		-0.069**
			(0.033)		(0.033)
Small Wildfire <0.5 KM			0.020***		0.021***
			(0.008)		(0.008)
Small Wildfire <1.0 KM			0.002		0.001
			(0.009)		(0.009)
SBB Outbreak <0.1 KM				0.010	0.007
				(0.009)	(0.009)
SBB Outbreak <0.5 KM				0.050***	0.050***
				(0.008)	(0.008)
SBB Outbreak <1.0 KM				0.051***	0.053***
				(0.009)	(0.009)
Percent Non Forested	0.001*	0.001**	0.001*	0.001**	0.001**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Percent Forested	-0.003***	-0.003***	-0.003***	-0.003***	-0.003***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Winter Temperature	-0.050***	-0.049***	-0.050***	-0.073***	-0.071***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Winter Precipitation	0.007***	0.006***	0.007***	0.009***	0.009***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Summer Temperature	-0.010	-0.012	-0.009	0.026	0.023
	(0.018)	(0.018)	(0.018)	(0.019)	(0.019)
Summer Precipitation	-0.020***	-0.019***	-0.020***	-0.020***	-0.019***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Elevation	-0.001***	-0.001***	-0.001***	-0.001***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Ln(Incrpt. City Distance)	-0.115***	-0.116***	-0.112***	-0.112***	-0.111***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Ln(Coast Distance)	-0.027***	-0.025***	-0.027***	-0.023***	-0.021***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Ln(Inland Water Distance)	-0.074***	-0.072***	-0.074***	-0.074***	-0.073***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Ln(Primary Road Distance)	0.025***	0.024***	0.025***	0.022***	0.021***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Ln(Secondary Road Distance)	0.014*	0.016**	0.014**	0.015**	0.017**
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Ln(School Distance)	0.045***	0.046***	0.045***	0.044***	0.046***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Ln(Parcel Size)	0.083***	0.082***	0.083***	0.088***	0.087***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)

VARIABLES	(1) No Disturbance	(2) Large Wildfire	(3) Small Wildfire	(4) SBB	(5) All Disturbance
Home Age	-0.006***	-0.005***	-0.006***	-0.006***	-0.006***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Bedrooms	0.039***	0.040***	0.038***	0.038***	0.039***
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Bathrooms	0.107***	0.107***	0.106***	0.106***	0.106***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Stories	-0.059***	-0.058***	-0.058***	-0.058***	-0.057***
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Ln(Home Square Feet)	0.514***	0.513***	0.514***	0.512***	0.511***
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Year2010	0.415***	0.414***	0.414***	0.403***	0.402***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Kenai	-0.043***	-0.046***	-0.039***	-0.023*	-0.022
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Homer	0.200***	0.197***	0.201***	0.224***	0.221***
	(0.039)	(0.039)	(0.039)	(0.039)	(0.039)
Seldovia	-0.258***	-0.237***	-0.249***	-0.270***	-0.244***
	(0.067)	(0.067)	(0.068)	(0.067)	(0.068)
Seward	0.528***	0.513***	0.526***	0.402***	0.386***
	(0.043)	(0.043)	(0.043)	(0.045)	(0.045)
Constant	8.623***	8.644***	8.608***	7.900***	7.915***
	(0.282)	(0.283)	(0.282)	(0.292)	(0.294)
n	8796	8796	8796	8796	8796
R-square	0.596	0.597	0.596	0.600	0.602
F	509.84***	455.00***	455.21***	461.22***	380.27***

Robust standard errors in parentheses

** p<0.10, ** p<0.05, *** p<0.01*

[a] Large wildfires are defined as > 3.3 ha, [b] Small wildfires are defined as < 3.3 ha

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Table 3.1. Descriptive statistics

	Obs	Mean	Std. Dev.	Min	Max	Data source
Large Wildfire [a] <0.1 KM	8796	0.002	0.049	0.0	1.0	AFS 2012
Large Wildfire <0.5 KM	8796	0.003	0.058	0.0	1.0	AFS 2012
Large Wildfire <1.0 KM	8796	0.011	0.107	0.0	1.0	AFS 2012
Small Wildfire [b] <0.1 KM	8796	0.013	0.114	0.0	1.0	AFS 2012
Small Wildfire <0.5 KM	8796	0.308	0.462	0.0	1.0	AFS 2012
Small Wildfire <1.0 KM	8796	0.643	0.479	0.0	1.0	AFS 2012
SBB Outbreak <0.1 KM	8796	0.339	0.473	0.0	1.0	USFS 2012
SBB Outbreak <0.5 KM	8796	0.490	0.500	0.0	1.0	USFS 2012
SBB Outbreak <1.0 KM	8796	0.647	0.478	0.0	1.0	USFS 2012
Percent Non Forested	8796	8.341	12.841	0.0	95.0	NLCD 2001
Percent Forested	8796	51.962	18.372	0.0	98.0	NLCD 2001
Winter Temperature	8796	-6.466	1.748	-8.0	-1.0	SNAP 2012
Winter Precipitation	8796	38.080	33.460	19.0	177.0	SNAP 2012
Summer Temperature	8796	12.909	0.443	11.0	15.0	SNAP 2012
Summer Precipitation	8796	41.895	12.650	31.0	96.0	SNAP 2012
Elevation	8796	61.895	53.608	1.0	462.0	NED 2012
Ln(Incrptd. City Distance)	8796	2.321	0.733	-0.4	4.5	KPB 2012
Ln(Coast Distance)	8796	1.504	1.405	-6.9	3.7	KPB 2012
Ln(Inland Water Distance)	8796	-0.272	1.651	-6.9	3.6	KPB 2012
Ln(Primary Road Distance)	8796	0.284	1.345	-3.7	3.6	KPB 2012
Ln(Secondary Road Distance)	8796	-2.799	0.644	-6.2	2.4	KPB 2012
Ln(School Distance)	8796	1.207	0.776	-3.2	3.1	KPB 2012
Ln(Parcel Size)	8796	-0.505	0.918	-2.8	4.2	KPB 2012
Home Age	8796	26.570	11.444	11.0	107.0	KPB 2012
Bedrooms	8796	3.146	0.448	1.0	6.0	KPB 2012
Bathrooms	8796	1.816	0.691	1.0	8.0	KPB 2012
Stories	8796	1.398	0.433	1.0	4.8	KPB 2012
Ln(Home Square Feet)	8796	7.417	0.414	5.5	9.2	KPB 2012
Kenai	8796	0.251	0.433	0	1	KPB 2012
Homer	8796	0.069	0.253	0	1	KPB 2012
Seldovia	8796	0.020	0.140	0	1	KPB 2012
Soldotna	8796	0.559	0.496	0	1	KPB 2012
Seward	8796	0.101	0.302	0	1	KPB 2012

[a] Large wildfires are defined as > 3.3 ha, [b] Small wildfires are defined as < 3.3 ha

Table 3.2. Ln(assessed property values), natural disturbance distance variables

VARIABLES	(1) OLS	(2) Spatial Lag	(3) Spatial Error	(4) Spatial Mixed
Rho		0.989***		0.940***
		(0.008)		(0.034)
Lambda			0.994***	0.984***
			(0.004)	(0.011)
Large Wildfire [a] <0.1 KM	0.227***	0.163**	0.212***	0.171**
	(0.059)	(0.069)	(0.078)	(0.077)
Large Wildfire <0.5 KM	0.184**	0.057	0.143**	0.097
	(0.090)	(0.078)	(0.066)	(0.065)
Large Wildfire <1.0 KM	0.058	-0.080**	0.005	-0.047
	(0.041)	(0.034)	(0.047)	(0.046)
Small Wildfire [b] <0.1 KM	-0.069**	-0.067**	-0.063**	-0.057*
	(0.033)	(0.030)	(0.031)	(0.030)
Small Wildfire <0.5 KM	0.021***	0.021***	0.027***	0.024***
	(0.008)	(0.007)	(0.008)	(0.008)
Small Wildfire <1.0 KM	0.001	0.001	0.010	0.008
	(0.009)	(0.008)	(0.009)	(0.009)
SBB Outbreak <0.1 KM	0.007	0.008	0.007	0.005
	(0.009)	(0.009)	(0.010)	(0.010)
SBB Outbreak <0.5 KM	0.050***	0.037***	0.042***	0.036***
	(0.008)	(0.008)	(0.009)	(0.009)
SBB Outbreak <1.0 KM	0.053***	0.031***	0.029***	0.021**
	(0.009)	(0.008)	(0.009)	(0.009)
Percent Non Forested	0.001**	0.002***	0.002***	0.001**
	(0.001)	(0.001)	(0.001)	(0.001)
Percent Forested	-0.003***	-0.002***	-0.002***	-0.002***
	(0.000)	(0.000)	(0.000)	(0.000)
Winter Temperature	-0.071***	-0.033***	-0.046***	-0.023**
	(0.008)	(0.008)	(0.011)	(0.010)
Winter Precipitation	0.009***	0.006***	0.007***	0.006***
	(0.001)	(0.001)	(0.001)	(0.001)
Summer Temperature	0.023	0.027	0.004	0.004
	(0.019)	(0.018)	(0.020)	(0.019)
Summer Precipitation	-0.019***	-0.014***	-0.019***	-0.014***
	(0.002)	(0.002)	(0.002)	(0.002)
Elevation	-0.001***	-0.001***	-0.001***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Ln(Incrptd. City Distance)	-0.111***	-0.049***	-0.124***	-0.077***
	(0.007)	(0.007)	(0.010)	(0.010)
Ln(Coast Distance)	-0.021***	-0.014***	-0.036***	-0.028***
	(0.005)	(0.005)	(0.006)	(0.006)
Ln(Inland Water Distance)	-0.073***	-0.064***	-0.085***	-0.075***
	(0.003)	(0.003)	(0.004)	(0.004)
Ln(Primary Road Distance)	0.021***	0.010***	0.009**	0.002
	(0.003)	(0.003)	(0.004)	(0.004)
Ln(Second. Road Distance)	0.017**	0.019***	0.024***	0.023***
	(0.007)	(0.007)	(0.007)	(0.007)
Ln(School Distance)	0.046***	0.009*	0.029***	0.006
	(0.005)	(0.005)	(0.007)	(0.007)

Table 3.2 Continued

VARIABLES	(1) OLS	(2) Spatial Lag	(3) Spatial Error	(4) Spatial Mixed
Ln(Parcel Size)	0.087***	0.079***	0.095***	0.092***
	(0.006)	(0.006)	(0.005)	(0.005)
Home Age	-0.006***	-0.005***	-0.005***	-0.005***
	(0.000)	(0.000)	(0.000)	(0.000)
Bedrooms	0.039***	0.041***	0.042***	0.043***
	(0.009)	(0.008)	(0.008)	(0.008)
Bathrooms	0.106***	0.100***	0.099***	0.097***
	(0.008)	(0.007)	(0.007)	(0.006)
Stories	-0.057***	-0.056***	-0.050***	-0.051***
	(0.009)	(0.009)	(0.009)	(0.008)
Ln(Home Square Feet)	0.511***	0.500***	0.506***	0.501***
	(0.013)	(0.012)	(0.012)	(0.012)
Year2010	0.402***	-0.001	0.952	0.196
	(0.001)	(0.007)	(1.16)	(0.421)
Kenai	-0.02	-0.013	-0.023	-0.015
	(0.013)	(0.013)	(0.020)	(0.020)
Homer	0.221***	0.150***	0.166***	0.125***
	(0.039)	(0.038)	(0.046)	(0.045)
Seldovia	-0.244***	0.002	-0.257***	-0.113
	(0.068)	(0.067)	(0.090)	(0.088)
Seward	0.386***	0.216***	0.360***	0.256***
	(0.045)	(0.043)	(0.059)	(0.058)
Constant	7.915***	-3.604***	7.235***	-2.889***
	(0.294)	(0.294)	(1.23)	(0.617)
Sigma		0.312***	0.310***	0.305***
		(0.004)	(0.002)	(0.002)
Observations	8,796	8,796	8,796	8,796
R-squared	0.602			
Log-likelihood	-2658.658	-2274.141	-2223.735	-2093.629
LR chi2 (vs. OLS)		769.034	869.845	1130.057
P-value		(< 0.01)	(< 0.01)	(< 0.01)
LR chi2 (vs. Spatial Lag)				361.024
P-value				(< 0.01)
LR chi2 (vs. Spatial Error)				260.212
P-value				(< 0.01)

Robust standard errors in parentheses

**p<0.1 **p<0.05 ***p<0.01*

[a] Large wildfires are defined as > 3.3 ha, [b] Small wildfires are defined as < 3.3 ha

Table 3.3. Ln(assessed property values), short-term and long-term effects

VARIABLES	(1) OLS	(2) Spatial Lag	(3) Spatial Error	(4) Spatial Mixed
Rho		0.988***		0.941***
		(0.008)		(0.034)
Lambda			0.994***	0.984***
			(0.004)	(0.011)
Large Wildfire [a] <0.1 KM 1-5yr	0.171**	0.134	0.166	0.141
	(0.080)	(0.096)	(0.101)	(0.099)
Large Wildfire <0.1 KM 6-20yr	0.247***	0.203**	0.226*	0.193*
	(0.077)	(0.083)	(0.116)	(0.114)
Small Wildfire <0.1 KM 1-5yr	-0.120**	-0.095**	-0.092**	-0.076*
	(0.048)	(0.043)	(0.046)	(0.045)
Small Wildfire [b] <0.1 KM 6-20yr	-0.038	-0.046	-0.045	-0.045
	(0.045)	(0.041)	(0.041)	(0.040)
Small Wildfire <0.5 KM 1-5yr	0.017	0.017*	0.029**	0.026**
	(0.010)	(0.010)	(0.011)	(0.011)
Small Wildfire <0.5 KM 6-20yr	0.023**	0.024***	0.022**	0.021**
	(0.009)	(0.009)	(0.010)	(0.010)
SBB Outbreak 0.1-1 KM 1-5yr	0.052***	0.035***	0.028***	0.022**
	(0.009)	(0.008)	(0.010)	(0.010)
SBB Outbreak 0.1-1 KM 6-20yr	0.064***	0.037***	0.042***	0.030***
	(0.008)	(0.008)	(0.009)	(0.009)
Percent Non Forested	0.001**	0.002***	0.002***	0.001***
	(0.001)	(0.001)	(0.001)	(0.001)
Percent Forested	-0.003***	-0.002***	-0.002***	-0.002***
	(0.000)	(0.000)	(0.000)	(0.000)
Winter Temperature	-0.063***	-0.027***	-0.043***	-0.020*
	(0.008)	(0.007)	(0.010)	(0.010)
Winter Precipitation	0.008***	0.006***	0.007***	0.005***
	(0.001)	(0.001)	(0.001)	(0.001)
Summer Temperature	0.016	0.017	-0.002	-0.001
	(0.018)	(0.017)	(0.020)	(0.019)
Summer Precipitation	-0.020***	-0.014***	-0.020***	-0.015***
	(0.002)	(0.002)	(0.002)	(0.002)
Elevation	-0.001***	-0.001***	-0.001***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Ln(Incrptd. City Distance)	-0.110***	-0.049***	-0.125***	-0.078***
	(0.007)	(0.007)	(0.010)	(0.010)
Ln(Coast Distance)	-0.021***	-0.013***	-0.036***	-0.028***
	(0.005)	(0.005)	(0.006)	(0.006)
Ln(Inland Water Distance)	-0.073***	-0.062***	-0.085***	-0.074***
	(0.003)	(0.003)	(0.004)	(0.004)
Ln(Primary Road Distance)	0.022***	0.011***	0.010**	0.003
	(0.003)	(0.003)	(0.004)	(0.004)
Ln(Secondary Road Distance)	0.015**	0.021***	0.025***	0.023***
	(0.007)	(0.007)	(0.007)	(0.007)
Ln(School Distance)	0.046***	0.010**	0.027***	0.005
	(0.005)	(0.005)	(0.007)	(0.007)
Ln(Parcel Size)	0.086***	0.076***	0.094***	0.091***
	(0.006)	(0.006)	(0.005)	(0.005)

Table 3.3 Continued

VARIABLES	(1) OLS	(2) Spatial Lag	(3) Spatial Error	(4) Spatial Mixed
Home Age	-0.006***	-0.005***	-0.005***	-0.005***
	(0.000)	(0.000)	(0.000)	(0.000)
Bedrooms	0.040***	0.042***	0.043***	0.044***
	(0.009)	(0.008)	(0.008)	(0.008)
Bathrooms	0.106***	0.100***	0.099***	0.097***
	(0.008)	(0.007)	(0.007)	(0.006)
Stories	-0.057***	-0.055***	-0.050***	-0.050***
	(0.009)	(0.009)	(0.009)	(0.008)
Ln(Home Square Feet)	0.511***	0.500***	0.506***	0.501***
	(0.013)	(0.012)	(0.012)	(0.012)
Year2010	0.404***	0.002	0.921	0.191
	(0.007)	(0.008)	(1.160)	(0.425)
Kenai	-0.026*	-0.020	-0.027	-0.019
	(0.013)	(0.013)	(0.020)	(0.020)
Homer	0.221***	0.142***	0.168***	0.125***
	(0.039)	(0.038)	(0.046)	(0.045)
Seldovia	-0.245***	0.015	-0.259***	-0.110
	(0.067)	(0.066)	(0.090)	(0.088)
Seward	0.434***	0.235***	0.392***	0.278***
	(0.044)	(0.042)	(0.059)	(0.058)
Constant	8.107***	-3.429***	7.403***	-2.773***
	(0.286)	(0.287)	(1.225)	(0.615)
Sigma		0.312***	0.311***	0.305***
		(0.004)	(0.002)	(0.002)
Observations	8,796	8,796	8,796	8,796
R-squared	0.600			
Log-likelihood	-2672.363	-2284.612	-2233.374	-2102.036
LR chi2 (vs. OLS)		769.034	880.177	1142.653
P-value		(< 0.01)	(< 0.01)	(< 0.01)
LR chi2 (vs. Spatial Lag)				365.152
P-value				(< 0.01)
LR chi2 (vs. Spatial Error)				262.676
P-value				(< 0.01)

Robust standard errors in parentheses

**p<0.1 **p<0.05 ***p<0.01*

[a] Large wildfires are defined as > 3.3 ha, [b] Small wildfires are defined as < 3.3 ha

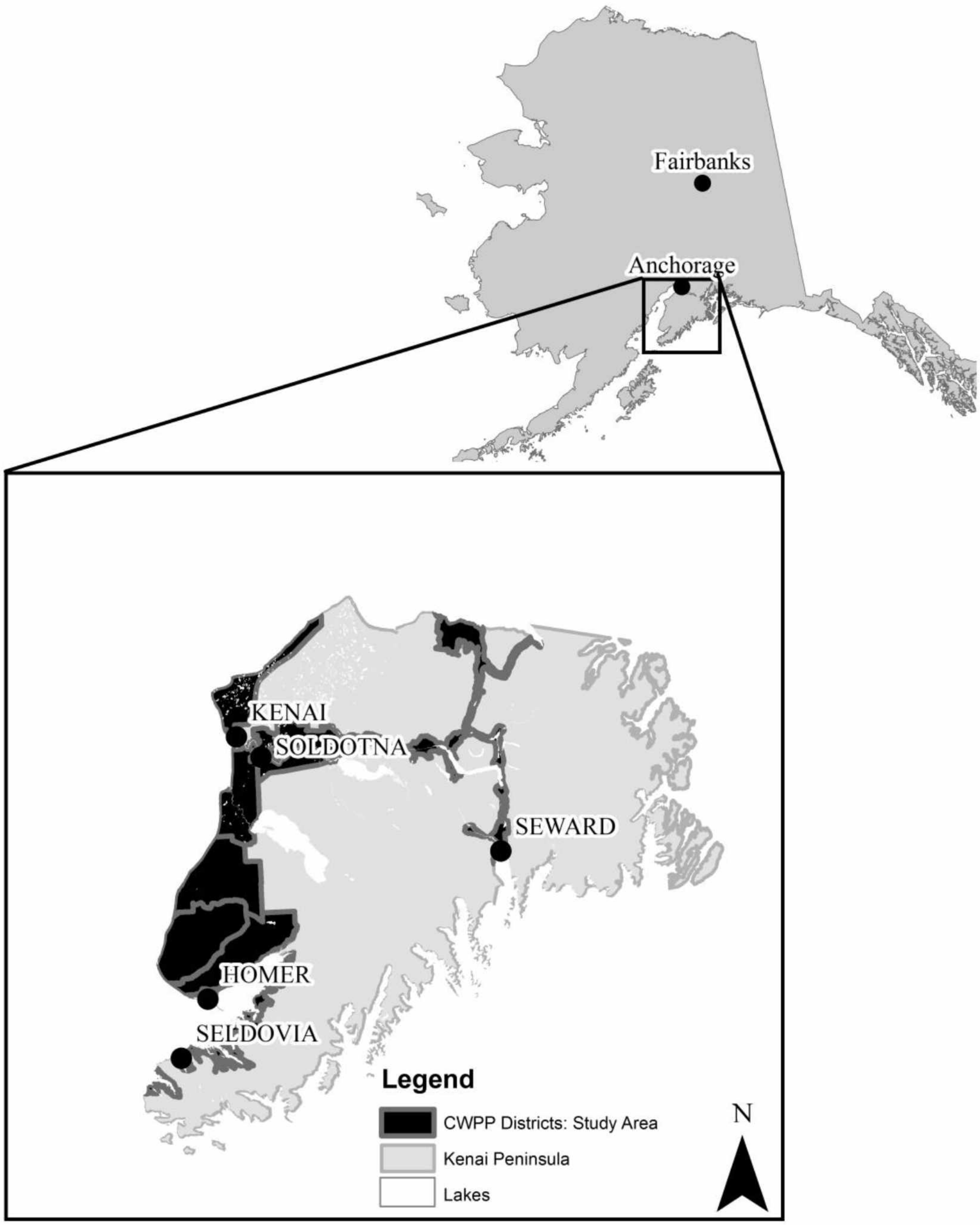

Figure 3.1. Kenai Peninsula and Study Area.

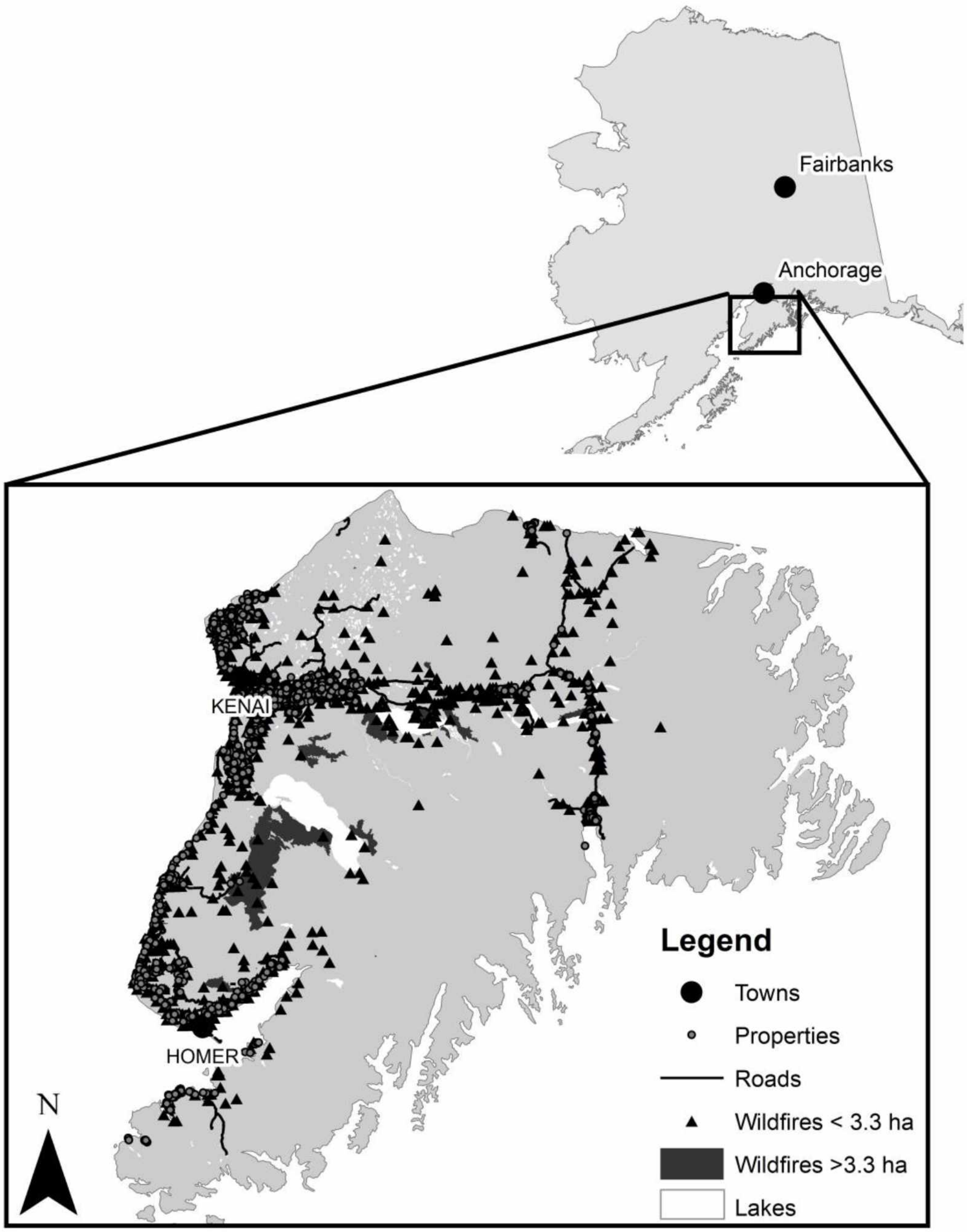

Figure 3.2. Wildfires on the Kenai Peninsula (1990-2010).

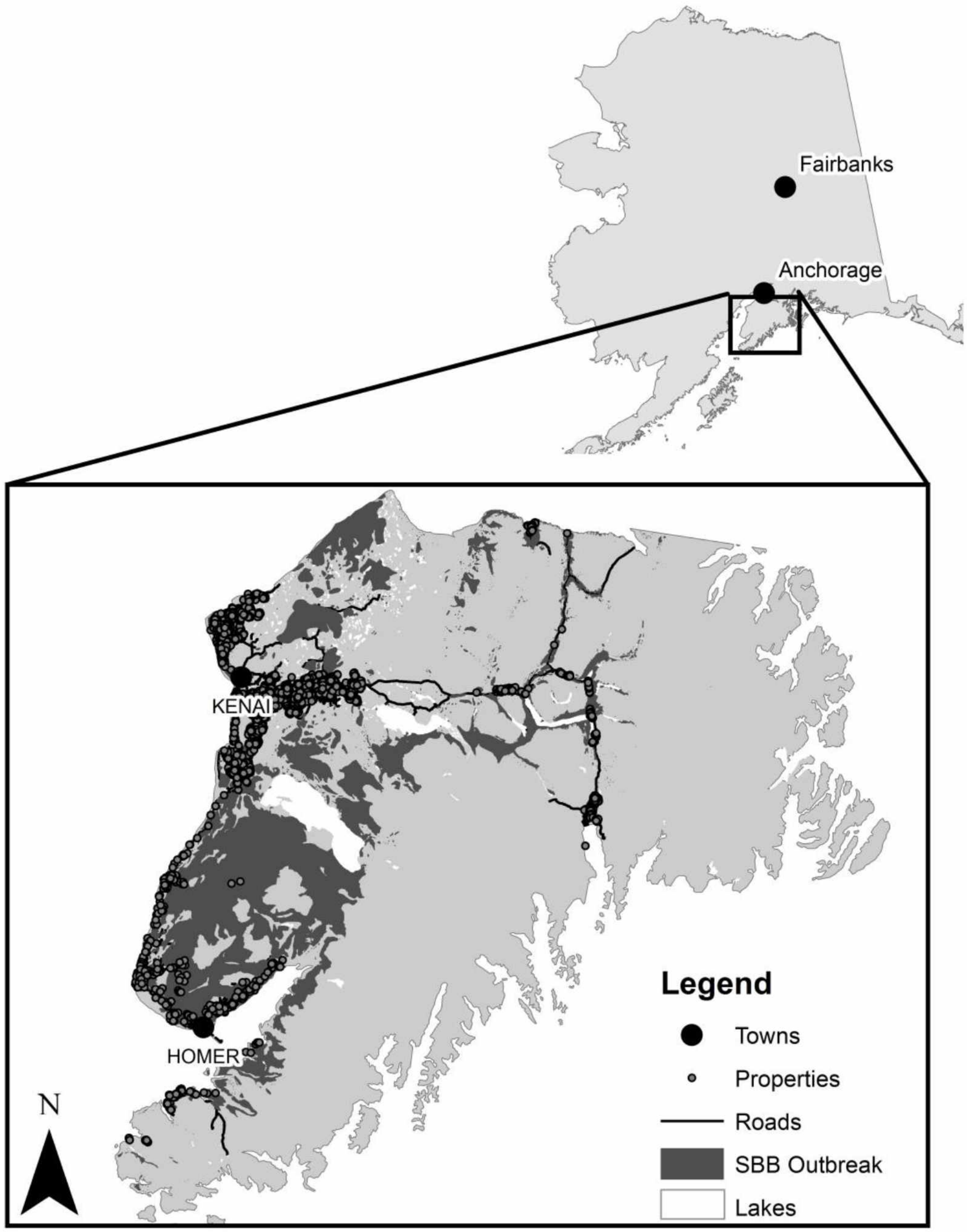

Figure 3.3. Spruce Bark Beetle Outbreak on the Kenai Peninsula (1989-2010).

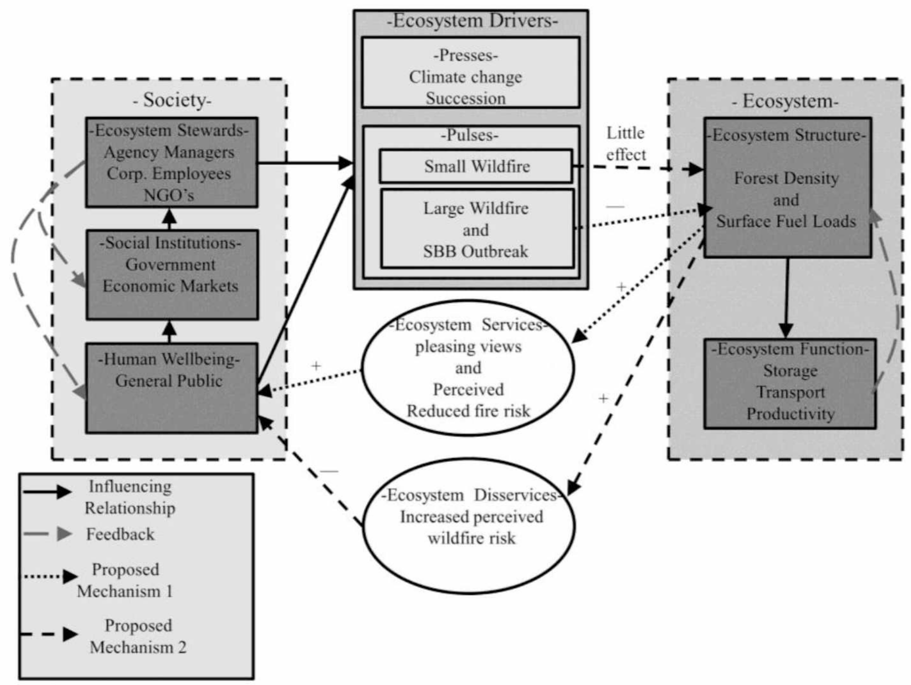

Figure 3.4. Conceptual framework depicting the relationship between SBB outbreak, large wildfires (> 3.3 ha), small wildfires (< 3.3 ha) and property values, an indicator of human well-being, in the WUI of the western Kenai Peninsula, AK, as described in chapter 3. Also included are proposed mechanisms for the effects of different natural disturbance types on property values. In proposed mechanism 1, wildfires > 3.3 ha and SBB outbreak decrease forest density, opening aesthetically pleasing views. Wildfires > 3.3 ha and salvage logging associated with SBB outbreak may also be perceived to reduce fuels decreasing wildfire risk. Aesthetically pleasing views and perceived reductions in wildfire risk increase property values. In proposed mechanism 2, wildfires < 3.3 ha have little effect on forest density or surface fuel loads. However, these wildfires remind people of the wildfire risk, reducing property values

Footnotes

[i] See for example Can (1990), Dubin et al. (1999), Bowen et al. (2001), Kim et al. (2003), Brasington & Hite (2005), Donovan et al. (2007), Small & Steimetz (2007), Mueller & Loomis (2008), Anselin & Garcia (2009), Osland (2010), Brady & Irwin (2011), and Ham et al. (2012).

[ii] All distances included in analysis were calculated as the distances from points representing the centroids of each property in our sample to the closest above features. These were calculated using Arc GIS Desktop 10.0 (ESRI, 2011).

[iii] To create the matrices necessary for modeling spatial spillovers, we calculated the x,y coordinates for the centroid of each property using Arc GIS Desktop 10.0 (ESRI, 2011). Coordinates were converted into a text file and imported into R statistical software (R Development Core Team, 2012). Using the spatial package "Fields" to calculate the Euclidian distances between all of the centroids in km, we generated a distance matrix for 2001 and 2010 (Furrer et al. 2009). We then used Stata (2011) software to aggregate the matrices into one with the two distance matrices on the diagonal and the rest filled with null values. We then calculate the inverse distance and row-standardize the matrix.

[iv] We use Jeanty's (2010) Stata code *spmlreg* to run our models on the Social Science Gateway hosted by Cornell University and funded by the NSF grant SES-0922005.

[v] We use Hendry's general-to-specific (Gets) approach outlined by Florax et al. (2003) to choose the statistically preferred econometric model. The Gets approach is robust to anomalies in the data generating process as discussed in Mur and Angulo (2009).

[vi] We use the standard transformation of 100*[exp(β)-1] for interpreting estimated coefficients for dummy variables (Wooldridge 2009).

Chapter 4

General Conclusions

4.1 Introduction

The human consumption of ecosystem services, or benefits provided to people by the surrounding environment, has led to increasing social, climate, and ecological change at local to global scales (Chapin et al. 2010, Chapin et al. 2011, Foley et al. 2005, MEA 2005). In the North American boreal forest, the effects of human-caused climate change have been substantial (ACIA 2005, Chapin et al. 2010, Flannigan et al. 2000). For example, the mean annual temperature has increased by 2 °C in interior Alaska between 1960 and 2000 (Chapin et al. 2003). As a result, natural disturbances such as wildfire and SBB outbreaks have increased in frequency and severity (Flannigan et al. 2009, Weber & Flannigan 1997). Changes to these boreal drivers will likely alter post-wildfire forest regeneration, tree species assemblages, and the types, quality, and quantity of ecosystem services provisioned for people (Johnstone & Chapin 2006, Johnstone et al. 2010, Mann et al. 2012). To maintain the continued provision of ecosystem services that form the foundation for human well-being in the North American boreal system, future emphasis must be placed on implementing management strategies guided by ecosystem stewardship principles and fostering human-environment interactions that better sustain long-term environmental capacity (Chapin et al. 2008, Liu et al. 2007, Rockström et al. 2009).

In the North American boreal system, changing the ways people interact with their surrounding environment will likely involve innovative solutions to novel social-ecological challenges and capitalizing on opportunities for win-win solutions as they arise (Chapin et al. 2006). However, recognizing challenges and opportunities, and implementing ecosystem stewardship-based strategies will require better understanding the complex nature of boreal SES structure and function. Throughout this thesis, I have adapted an existing SESs framework to capture system-specific boreal conditions (Figure 4.1) (Collins et al. 2010). We then applied portions of this framework to evaluate complex social and ecological processes in the boreal forest of the Kenai Peninsula, Alaska. In this concluding section I will synthesize what we have learned, over the previous two chapters, and develop generalizable axioms that may help people innovatively implement ecosystem stewardship strategies to guide sustainable boreal human-environment interactions.

4.2 Chapter Synthesis

4.2.1 Chapter 2

In chapter two, we applied part of the adapted SESs framework to evaluate the magnitude of linked disturbance interactions in a boreal setting and the ecological implications of those interactions (Figure 4.2). Specifically, we asked: Has the 1990's SBB outbreak on the western Kenai Peninsula, Alaska altered the probability of subsequent large wildfire (> 500 ha) and the probability of small wildfires (< 500 ha)? We found that factors controlling the probability of large wildfire were radically different from those controlling small wildfires. The occurrence of 1990's SBB outbreak was associated with increases in the probability of large wildfire. Further, this positive effect of the SBB outbreak on the probability of large wildfire remained when the outbreak variable was scaled by the number of years that the outbreak persisted. Conversely, the 1990's SBB outbreak had little influence on the probability of small wildfires. Important control variables for small wildfires were related to human activity, such as ignition sources, and wildfire suppression.

The results presented in this chapter largely contrast with past work on the topic. Historically, it appears SBB outbreaks had little or no influence on wildfire. Using cross-system comparisons, we provide several speculative hypotheses to explain the conflicting nature of our findings. First, we hypothesize that the 1990's SBB outbreak now further amplifies the positive effects that warming trends already have on the probability of large wildfire. Throughout the boreal system, the frequency, annual area burned, and severity of wildfires have increased markedly. The amplifying effects of bark beetle outbreak on climate have been documented in other studies. In British Columbia, forest surface temperatures were estimated to be 1 °C higher in bark beetle outbreaks, as compared to non-affected stands. Secondly, significant increases in surface-fuel loads, including all size classes, have been documented following the 1990's outbreak. This diverges from studies on bark beetle-wildfire interactions in the Rocky Mountains where a lack of connection between outbreak and subsequent wildfire has been attributed to little change in surface fuels.

The results of this study help to improve our conceptual understanding of linked disturbance interactions and prioritize future research needs to advance knowledge on the concept. The drivers that control whether linked disturbance interactions are “turned on” are still poorly understood. Work is needed to identify common controlling drivers across a number of systems and characterize the nature of their influence. Examples include the influence of people, surface fuel dynamics, and changing climate. Secondly, this study provides valuable insight into how a changing boreal wildfire regime may be further altered by the expansion of another natural disturbance that responds positively to warming trends--SBB outbreak. Our study suggests that changes in wildfire may be amplified when in interaction with SBB outbreak. Ecologically, this has important implications for ecosystem structure, including forest composition, permafrost dynamics, and species distributions, as well as ecosystem function, such as carbon storage, nutrient fluxes and transport, and productivity.

4.2.2 Chapter 3

In chapter three, we used another portion of the adapted framework to quantify how the occurrence of wildfire and SBB outbreak on the Kenai Peninsula affect human well-being, as measured by the effects of disturbance on property values in the WUI (Figure 4.3). Specifically, we used spatial econometric techniques in a hedonic pricing framework to address the following questions: 1. What is the extent to which wildfires and the 1990’s SBB outbreak affect WUI property values? 2. How do relationships between natural disturbance and property values vary with distance from the property center? Does this relationship change with time since the disturbance occurred? We found that wildfires > 3.3 ha and the 1990's SBB outbreak were associated with increases in property values, when significant, and their effects magnified over time. Conversely, wildfires < 3.3 ha negatively influenced property values when very close to property center (< 0.1 km) and these effects dissipated with time. Finally, we found evidence of spatial spillover effects. In other words, disturbance effects on the value of one property affected neighboring property values.

The positive effects of wildfires > 3.3 ha and SBB outbreak on property values may appear counter-intuitive. However, the results of this study highlight the complex viewpoint people develop as they weigh the benefits of ecosystem services with the costs of ecosystem disservices that result from disturbance. We offer two hypotheses. First, it may be that wildfires > 3.3 ha and SBB outbreak are associated with increased property values because they reduce forest density around homes, improving views of the ocean and mountains beyond (Figure 4.4). Findings of past research lend support for this hypothesis (Flint 2006). The positive effects of large natural disturbances may dissipate as trees reestablish and eventually reduce views again. Secondly, we hypothesize that wildfires > 3.3 ha and SBB outbreak may decrease perceived risk of future wildfires while smaller wildfires do not. When wildfires > 3.3 ha burn and most vegetation is consumed, it is unlikely another wildfire will occur for perhaps hundreds of years. Conversely, smaller wildfires do not consume most of the vegetation. Instead, they likely only act as a reminder of wildfire risk, hence their negative effect on property values. While our research shows that the 1990's SBB outbreak has actually increased subsequent wildfire activity, a significant amount of salvage logging took place following the outbreak. Homeowners may perceive a decreased risk of future wildfire as a result of salvage logging.

This study highlights promising opportunities for introducing novel fuels reduction treatments that could let naturally caused wildfire burn more regularly while protecting life and property. Managers may garner more support for fuels treatments by designing them to enhance aesthetically pleasing views around homes. Further, we provide ways to incentivize broader public participation and support by showing how the views enhanced as a result of treatments could increase property values. Finally, the spatial spillovers documented in this study might help managers show homeowners how their actions affect not only their own property values but their neighbors' as well. This could foster community cohesion and increase pressure on those in the neighborhood that are still resistant to treatments.

More generally, we use our findings to prioritize future research needs for better understanding complex human-natural disturbance interactions. We suggest that further work should focus on the ways in which humans perceive the consequences of natural disturbance, better assimilating ecological advancements into economic valuation studies, and integrating ecological and economic agents into single, more comprehensive analyses that can accommodate feedbacks and non-linear relationships.

4.3. Generalizable Axioms

After applying portions of the adapted framework to evaluate complex social and ecological processes in a changing boreal system, a set of generalizable axioms emerged that may help implement ecosystem stewardship-based management strategies to guide boreal human-environment interactions (Table 1). In general, they focus on recognizing challenges before they arise and proactively seizing opportunities in dynamic and changing boreal SESs (Folke et al. 2010, Folke et al. 2011, Olsson et al. 2010).

Axiom 1: As an ecosystem steward, spend half of your time thinking about the ecosystem you are involved in and the other half on the people in your constituency.

As ecosystem stewards implement strategies meant to change the way humans interact with their environment, it is not the ecosystem that is vocal, affected people are the ones that will share their opinions. When considering and developing new stewardship strategies, identify who the stakeholders are that will ultimately be affected. Engage them candidly from the beginning, face-to-face, and on equal footing (Armitage et al. 2008). Look for creative win-win solutions to challenging problems that incorporate ecologically important stewardship objectives with incentives that improve well-being for stakeholders. When attempting to understand the value system from which your stakeholders form their position, carefully consider both what they tell you, as well as their revealed preferences from econometric studies.

Findings from chapter three highlight the utility of this axiom. Naturally caused wildfires on the Kenai Peninsula are often suppressed for the important reason of protecting life and property. In the long-term, the active suppression of wildfire may actually prime forests for a future catastrophic wildfire event that cannot be effectively suppressed. Past work has shown that people on the Kenai Peninsula have had mixed reactions to the 1990's SBB outbreak (Flint 2006). However, using a revealed preference technique, we found that increasing property values in the WUI of the Kenai Peninsula are associated with the occurrence of wildfires > 3.3 ha and SBB outbreaks, potentially as a result of opening aesthetically pleasing views. The use of revealed preference techniques helped to identify new potential opportunities for implementing stewardship strategies. One might be able to engage homeowners to participate in fuels reduction treatments that could let naturally caused wildfire burn more regularly by designing the treatments to enhance views. Showing homeowners that treatments can increase their property values and improve human well-being may bolster their enthusiasm for the win-win solution.

The other half of this axiom is to pay attention to and understand the dynamics of the surrounding ecosystem. According to the adapted framework, the structure and function of the ecosystem and the associated provisioning of ecosystem services are at the core of human well-being (Collins et al. 2010). It is often as a direct result of changes in pressing and pulsing ecosystem drivers that the provision of ecosystem services, and thus human well-being, is affected (Turner et al. 2012). Characterizing the changing nature of presses and pulses will help to proactively identify challenges and opportunities. Spatial and temporal scales are a key ecological characteristic (Peterson et al. 1998). When ecosystems are considered, it is pulses that are normally at the center of human scrutiny. Their consequences are tangible and occur on temporal scales meaningful to people. However, it is often pressing drivers that set the stage and determine the magnitude of consequences associated with pulsing drivers (Smith et al. 2009). For example, in chapter two, linked disturbance interactions were likely mediated by the slow, incremental, but persistent increase in temperature. While hardly noticeable season-to-season, these increases in temperature have had a dramatic effect on the characteristics of wildfire and human well-being. When implementing ecosystem stewardship principles, considering pressing and pulsing drivers, the interactions between them, and their implications for ecosystems may yield important acumens.

Axiom 2: Social and ecological systems are dynamic and stochastic: Approach stewardship experimentally.

As an ecosystem steward, one must acknowledge that the insights into system structure and function learned today may not apply in the near future, and then may apply again in the far future (Cumming et al. 2012). For instance, historical SBB outbreaks likely did not affect wildfire on the Kenai Peninsula. It appears now, however, that they increase the probability of large wildfire. The point is that system dynamics can change quickly and unpredictably. This presents both challenges and opportunities for implementing ecosystem stewardship strategies. One challenge is that it is hard to predict how a given component of the SES will respond to strategies that foster change in human-environment interactions. Unanticipated consequences can occur non-linearly and perhaps more quickly than human institutions are structured to adjust (Cumming et al.

2006). As a result, developing and maintaining ecosystem stewardship approaches will require continual adaptation. This suggests that experimentation and the use of simulation modeling are important; think big but experiment small. Identify a manageable chunk of the SES where negative, unanticipated consequences will not be devastating, where the damage can be controlled. When no such chunk exists, use simulation modeling to evaluate potential outcomes of management strategies. If outcomes from experimentation or modeling efforts are not optimal, try again before scaling up. While a given approach works, continue experimenting with others in case system dynamics change. The same dynamic, stochastic nature of social and ecological systems, that can cause challenges for implementing ecosystem stewardship-based strategies, also offer opportunities. It means that if the current trajectory of a given human-environment interaction is one of degradation, altering that trajectory, given the right leverage, is definitely possible. The trick is to alter trajectories productively.

Axiom 3: Use the best available science, but don't let it handcuff you.

Science has made important advancements in characterizing actors, drivers, and feedbacks of SESs and developed a number of valuable tools for their study (Berkes & Folke 1998, Chapin et al. 2009, Collins et al. 2010, Ostrom 2007). However, conceptual barriers continue to persist. Ecosystem stewards attempting to instigate change will benefit from being aware of and using the best available science, where applicable. However, when science does not provide certainty, do not become handcuffed to inaction. Critical advancements in our understanding of the boreal SESs on the Kenai

Peninsula have been made due to the actions of ecosystem stewards in scientifically uncertain conditions. Practitioner experience is at least as valuable as scientific understanding. Integrating science with practitioner experience will provide the most comprehensive foundation from which to make decisions in uncertain conditions. However, remember to manage the negative unanticipated consequences by testing approaches at small, controllable scales.

Axiom 4: The only panacea is money, time, and passion and there is never enough to go around.

No matter the context, you can always accomplish a greater amount with more money, more time in the day, and more passionate, dedicated people around you. Yet, we are all limited, to varying extents, by the resources available to us. This has two implications for implementing ecosystem stewardship-based management strategies. First, write grants, lots and lots of them. Whether you are an ecosystem manager with a local, state, or federal government agency, an academic, or work for a private corporation, there is grant money offered regularly. If you are truly passionate about changing the trajectory of human-environment interactions, then resources above what is regularly available at your position are necessary. Experimentation is expensive. Understanding complex systems, to the extent that we can, is even more costly. Be prepared for tight times, never lose sight of why you are committed, and don't lose hope. The second implication is to manage your expectations. There are no panacea solutions (Ostrom 2007). Subsequently, implementing ecosystem stewardship strategies will be a slow and incremental process that requires persistence. No individual contribution will completely alter trajectories of human-environment interactions in the boreal system, but the aggregate impacts of many individual efforts could be substantial.

4.4 Conclusion

The goal of this thesis was to adapt an existing SESs framework to better reflect local conditions of a changing boreal system and apply portions of that framework to evaluate complex social and ecological processes in a boreal setting. Finally, I synthesized the findings of those studies to develop general axioms for guiding the implementation of ecosystem stewardship-based strategies in boreal SESs. The use of the adapted framework as a diagnostic tool yielded substantial insight into system structure and function. It appears that the effects of rising temperatures on boreal wildfire may be further amplified when in interaction with SBB outbreaks--another natural disturbance that responds positively to warming trends. This finding has important implications for future boreal forest composition, tree species assemblages, and the provisioning of ecosystem services. Further, we found that large wildfires and SBB outbreak had counter-intuitive effects on property values in the WUI. These natural disturbances were associated with increases in property values. This suggests that there are opportunities to develop win-win solutions in the management of naturally-caused wildfire. Strategically developing fuels-reduction treatments that enhance views around homes could increase public enthusiasm for actions that allow naturally-caused wildfires to burn regularly, while still protecting life and property.

The findings of these two studies contributed to the development of generalizable axioms that may help to guide the implementation of ecosystem stewardship-based management of boreal human-environment interactions:

- As an ecosystem steward, spend half of your time thinking about the ecosystem you are involved in and the other half on the people in your constituency.
- Social and ecological systems are dynamic and stochastic: Approach stewardship experimentally.
- Use the best available science, but don't let it handcuff you.
- The only panacea is money, time, and passion and there is never enough to go around.

The purpose of presenting these axioms is to stimulate critical dialogue on the way in which people of the North American boreal forest, including scientists, the general public, elected officials, corporations, and ecosystem managers, approach their interaction with the surrounding environment and how we consider the implications of those interactions for fostering social-ecological sustainability in the boreal system.

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Table 4.1. Generalizable axioms for implementing ecosystem stewardship principles in a changing boreal social-ecological system and boreal examples highlighting axiom utility.

Generalizable Axiom	Boreal Example
Think about the ecosystem half the time and people for the other half.	Design fuel reduction treatments to maximize incentives that can garner public support.
SESs are dynamic and stochastic: Approach stewardship experimentally.	Relationship between SBB outbreak and wildfire has changed over time.
Use the best available science, but don't let it handcuff you.	SBB Mitigation Program and All Hands All Lands group merging available science with practitioner experience.
The only panacea is time, money, and passion.	Maintain moderate expectations, apply for grant money.

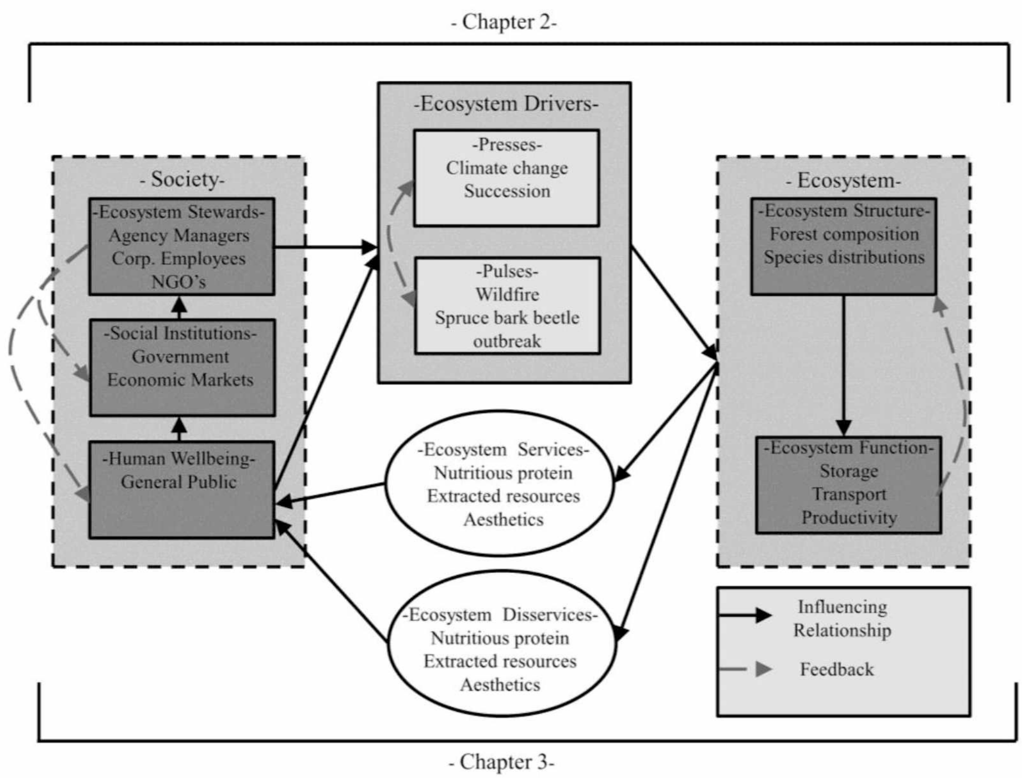

Figure 4.1. Conceptual framework of a social-ecological system originally developed by Collins et al. (2010). This version has been adapted to better represent boreal conditions and dynamics. Specific adaptations include differentiating and characterizing the influence of human institutions and incorporating ecosystem disservices in addition to ecosystem services.

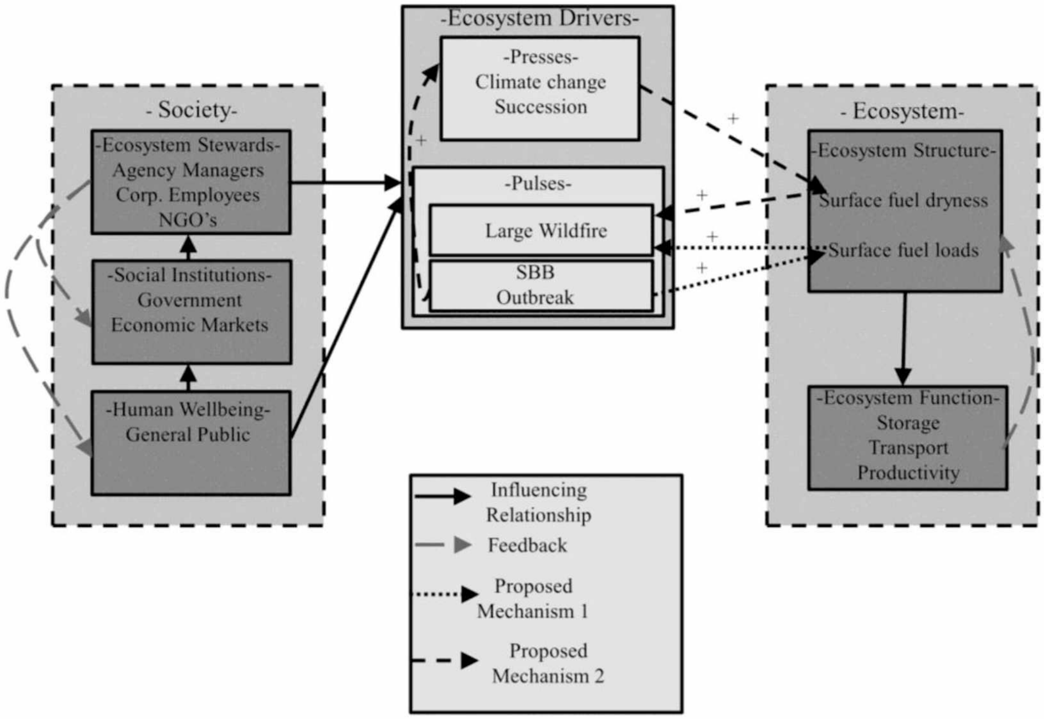

Figure 4.2. Conceptual framework depicting the relationship between SBB outbreak and subsequent large wildfire on the western Kenai Peninsula, AK, as described in chapter 2. Also included are proposed mechanisms for the effects of SBB outbreak on large wildfire. In proposed mechanism 1, SBB outbreak leads to an increase in surface fuel loads which increases the probability of subsequent large wildfire activity. In proposed mechanism 2, SBB outbreak further amplifies already occurring warming trends in the study area. This causes fuels to be drier, increasing the subsequent probability of large wildfire activity.

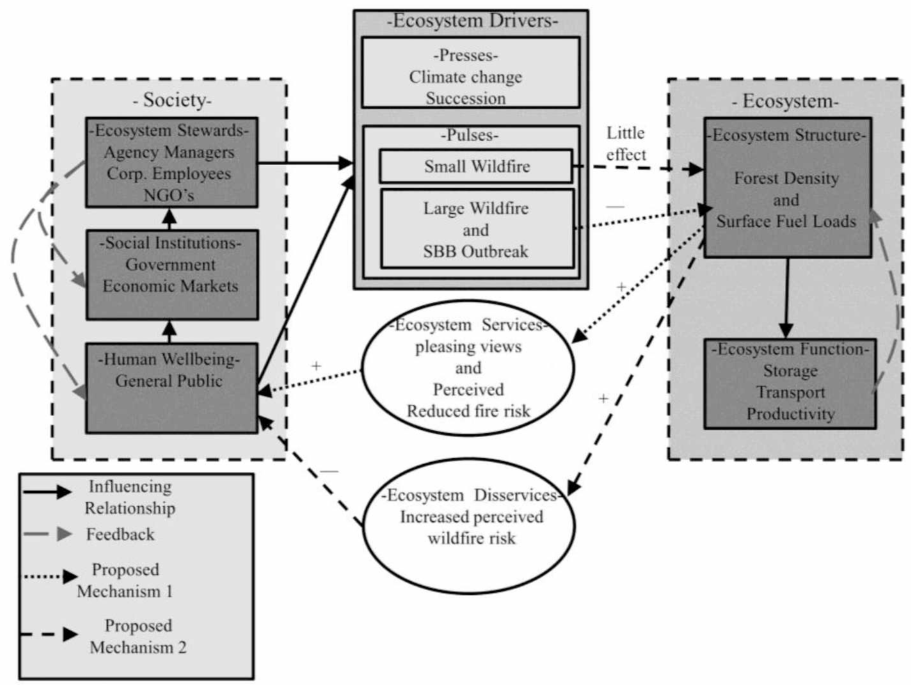

Figure 4.3. Conceptual framework depicting the relationship between SBB outbreak, large wildfires > 3.3 ha, small wildfires < 3.3 ha and property values, an indicator of human well-being, in the WUI of the western Kenai Peninsula, AK, as described in chapter 3. Also included are proposed mechanisms for the effects of different natural disturbance types on property values. In proposed mechanism 1, wildfires >3.3 ha and SBB outbreak decrease forest density, opening aesthetically pleasing views. Large wildfires and salvage logging associated with SBB outbreak may also be perceived to reduce fuels decreasing wildfire risk. Aesthetically pleasing views and perceived reductions in wildfire risk increase property values. In proposed mechanism 2, wildfires < 3.3 ha have little effect on forest density or surface fuel loads. However, these wildfires remind people of the wildfire risk, reducing property values.

Figure 4.4. Photograph of a home located in a forest where SBB outbreak occurred. Forest density was reduced, opening up views of Cook Inlet and mountains.